

## **A Fast-Time Simulation Tool for Analysis of Airport Arrival Traffic**

*Frank Neuman, Heinz Erzberger, and Larry A. Meyn*

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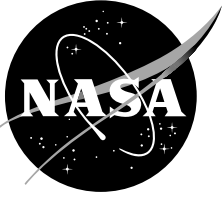
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## SYMBOLS

AAR	airport acceptance rate (set by TRACON)
ata	actual time of arrival at runway
ataFH	actual time of arrival at the freeze horizon
ATC	air-traffic control
CDM	collaborative decision-making
CTAS	Center TRACON Automation System
DDF	Delay Distribution Function ( Function that distributes delays between Center and TRACON)
DFW	Dallas/Ft. Worth airport
$\Delta$ DOC	direct operating cost (additional cost due to TMA commanded delays in the Center and TRACON)
dTmax	portion of the total delay computed in the Center that is completely assigned to the TRACON; the remainder assigned to the Center
etaFH	estimated time of arrival at a feeder fix
etaj	estimated arrival time at the jth runway, given no interfering traffic, $j = 0-2$ (3 runways)
eta3	minimum time of arrival (given no interfering traffic)
FAST	Final Approach Spacing Tool (a decision-support tool for terminal area controllers)
FCFS	first-come, first-served scheduling
fferrD	delay due to feeder fix arrival errors
fhD	delay due to freeze horizon arrival errors
FTS	fast-time simulation
GDP	ground-delay program
NE	northeast feeder fix to the DFW airport

NW	northwest feeder fix to the DFW airport
RBS	ration-by-schedule
SE	southeast feeder fix to the DFW airport
STA	scheduled time of arrival (a parameter used in TMA)
SW	southwest feeder fix to the DFW airport
TMA	Traffic Management Advisor (a decision-support tool for Center controllers)
TRACON	Terminal Radar Approach Control

## **DEFINITION OF TERMS**

Airline schedule: Gate-to-gate departure and arrival times assigned by the airlines.

Connectivity: A cost factor which has been mentioned in this report, but could not be computed because of limited information publicly available. One hundred percent connectivity means that all passengers who need to transfer have sufficient time to do so. This can be achieved, at a cost, by scheduling long times at the gates.

Freeze-horizon: Distance (or in 1996 time) to feeder fix where scheduled feeder-fix arrival times are frozen.

Normal traffic: Traffic not restricted by unusual conditions. Traffic that attempts to meet airline schedules; especially in hub airports it has many sharp traffic peaks.

Squared traffic: Around each traffic peak, it is proposed that the airlines assign new scheduled times of arrival at the freeze horizons (slots) spaced at equal intervals. By including some of the original low-density traffic skirts around the traffic peak, each new scheduled traffic peak is made into a rectangle.

Stream class: Separate routes for jets and other aircraft up to a merge point.

TMA schedule: If too many aircraft are scheduled by the airlines to arrive in a short interval of time, or if random arrival errors at the freeze horizon cause an airport to become overloaded, TMA delays aircraft to meet en-route and landing safety restrictions.

TRACON schedule: In the TRACON, aircraft are rescheduled by FAST including updated runway assignments as functions of actual feeder-fix arrival times.



# **A FAST-TIME SIMULATION TOOL FOR ANALYSIS OF AIRPORT ARRIVAL TRAFFIC**

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## **SUMMARY**

The basic objective of arrival sequencing and scheduling in air-traffic control automation is to match traffic demand and airport capacity while minimizing delays. The principle underlying practical sequencing and scheduling algorithms currently in use is referred to as first-come-first-served (FCFS). One of the tools developed by NASA is the Traffic Management Advisor (TMA), which the FAA has deployed at several hub airports. TMA is an element of the Center TRACON Automation System (CTAS), a suite of decision-support tools developed by NASA for controllers. Prior to deployment, the TMA scheduling software had to be tested in a real-time simulation, which was very manpower and time intensive; as a result, only relatively few traffic situations could be simulated. In order to estimate the statistical performance of the system we have written a fast-time simulation of the scheduling process built into TMA, which preserves TMA's important features, but does not involve human interaction, and which can perform many simulations in a short time. To use this simulation, we model the specific airport, the traffic, and especially the deviations from estimated arrival times. These times are measured at distances where Center controllers begin to regulate the traffic (freeze horizons), and at points close to the airport (feeder fixes) where TRACON controllers take over. This report reviews the development of the simulation and several earlier studies of scheduling algorithms that were evaluated using this simulation. In order to demonstrate another use of this method of fast-time simulation, we examine the effect on arrival delays of minimally altering arrival traffic schedules at a hub airport. It is assumed that the original airline arrival schedule for a hub airport with its multiple peaks is optimal from the airline standpoint. Without upsetting the multiple peak structure, it is proposed to reduce delays by using equally spaced slot assignments around each traffic peak. This preserves each traffic peak but spreads it out sufficiently to substantially reduce air-traffic management enforced delays. Fast-time simulation is used to evaluate the method in the presence of errors. Results show that this method can indeed achieve substantially reduced delays and improved arrival order.

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## INTRODUCTION

The continued growth of air traffic within the United States has led to increased congestion and delays in the terminal airspace surrounding the Nation's busier airports. The problem is exacerbated at hub airports, where air carriers schedule large numbers of flights to arrive and depart within short time periods, resulting in multiple traffic peaks during the day. To air carriers, hubbing makes good economic and competitive sense. At the same time, however, hubbing operations lead to many overcapacity traffic peaks, which precipitate delays that can directly affect the economic efficiency of an air carrier's flight operations. To ensure that the safe capacity of the terminal area is not exceeded, air-traffic management (ATM) often places restrictions on arrival flights that are transitioning from en route to terminal airspace. The constraint of arrival traffic is commonly referred to as arrival flow management.

Air-traffic management automation tools used in arrival flow management are primarily based on the first-come-first-served (FCFS) principle. One of the tools designed by NASA is the traffic management advisor (TMA), which is now used by the FAA at several hub airports. Aircraft are scheduled so that they arrive in first-come-first-served order based on an estimated time of arrival at the runway (ETA) at about 200 miles from touchdown (the freeze horizon). For moderate traffic densities, and no unusual weather conditions, FCFS orders the arrivals approximately in the order desired by the airlines. When, however, too many aircraft are scheduled by the airlines to arrive in a short interval of time, it is necessary for TMA to delay aircraft in both Center and TRACON airspace, and this process can change the TMA scheduled landing order substantially from the airline-desired order.

As part of its collaborative arrival planning research and development program, NASA is exploring what airlines and the FAA can do jointly to reduce the arrival delays that presently occur in hub airport traffic. The ground delay program (GDP) will be used as a model for the various aspects of accomplishing the task, without affecting traffic connectivity. Decreased connectivity is a cost item, which only airlines can compute by knowing, at least statistically, passenger destinations. The airline must estimate both the probability that a passenger misses his connection and the cost of his missing it. One important question is: How much can the airlines change schedules to avoid the sharp traffic peaks in the daily traffic in order to reduce delays without passengers missing their connections? We do not have connectivity data with which to study this question in detail. Hence we have chosen an example for traffic improvement, which only slightly changes the arrival times, and which therefore should not affect connectivity.

Since real-time simulations and field tests are expensive to conduct and slow to produce statistical results, fast-time simulation is used for this initial study.

## **BASIC ELEMENTS OF A STOCHASTIC ARRIVAL TRAFFIC SCHEDULING SIMULATION**

We will first deal with a specific fast-time simulation, that of the Noon Balloon traffic peak in 1996 at Dallas Fort Worth Airport. The simulation models the runways, the traffic, and the scheduler used in TMA. Next, we will discuss how this simulation may be adapted to study traffic at different airports and in different traffic situations. A diagram of the overall process and its components is shown in figure 1.

### **Airport Simulation**

The traffic situation is modeled for an airport with four feeder fixes and three independent runways available for landings. For this example the most common configuration used at DFW in 1996 was chosen: runways 18, 17, and 13. Since 1996, DFW has added a fourth runway, which has somewhat alleviated the delays during rush periods such as the Noon Balloon. In spite of this, American Airlines plans to reduce the peak magnitudes and double the number of the peaks. However, the three-runway configuration at DFW remains important because of its use during certain adverse weather conditions. The three-runway case was modeled according to the landing practices that existed in 1996 (fig. 2(a)). Jets and turboprops arrive at each of the four feeder fixes in two independent streams (fig. 2(b)); the figure shows the traffic during the Noon Balloon time interval. The assumption of two streams per feeder fix is necessary in order to simulate the in-trail constraints in the Center. Inside TRACON, aircraft have different flight times and routes that depend on the specific entry feeder fix and landing runway threshold. Such flight times can only be achieved if controllers have to deal with few aircraft, which happens between traffic peaks. The preferred runway is modeled as the runway with a minimum flight time from the feeder fix.

The times given in table 1 for north flow and south flow of the traffic are the minimum times from feeder fix to runway threshold. The blank spots in the table are for flightpaths that are usually never chosen, and therefore no times are given. The data were taken from calculations performed by the TMA used in the field trial in 1996; the calculations were verified by flight data. It should be noted that, in the actual system, these times are calculated in real time to account for winds.

In the specific simulation considered here, the total delay between Center and TRACON was separated because we are interested in determining the interactions of airport arrival rate (AAR) and delay distribution function (DDF). This is accomplished by a delay distribution with a parameter  $dT_{max}$  and will be discussed briefly in the next section.

Depending on the type of investigation, either a synthetic airport or an existing airport may be simulated. Runways can also be removed from the model of an existing airport by setting the feeder-fix-to-runway-threshold times of the deactivated runways to large values. This will result in the scheduler avoiding those runways. Runways can also be added by adding another line to the matrix in table 1, where all values are likely to change somewhat. This would be done, for instance, if the intention was to simulate DFW with the fourth runway installed.

**Table 1. Minimum feeder fix to runway threshold times for three runways, sec**

	North flow					South flow				a/c type
	NW	NE	SW	SE		NW	NE	SW	SE	
36L	649	723	592	—	13R	590	—	—	950	Jets
35C	716	730	610	626	18R	665	730	860	960	
31R	820	645	—	621	17L	770	635	920	980	
36L	715	812	587	—	13R	650	—	820	—	Large
35C	804	—	608	650	18R	720	820	890	1050	Turbo-
31R	—	723	—	625	17L	850	710	790	900	props

When a traffic management system is to be newly installed at an airport, it is best to get data similar to those shown in table 1 from radar data taken during intervals of low traffic density. Flightpaths from each feeder fix to each possible runway threshold are established based on air-traffic controller experience. The choice of these paths and their minimum and maximum flight times are a matter of experience.

### Modeling Traffic

For this simulation, 1996 traffic is used, since detailed field test data are available. The density of the traffic at DFW has repeatable peaks, with periods of light traffic between peaks. The traffic peak, which we examined in detail, is the “Noon Balloon” at DFW, which was the time interval of the most prominent traffic peak at DFW. To get realistic answers, data were collected for six separate days in 1996 during which we were doing field tests: Thursday, 18 April; Friday, 26 April; Monday, 29 April; Tuesday, 30 April; Friday, 14 June; and Wednesday, 17 July. From the complete data set we abstracted the aircraft identification (ID), aircraft type (to derive the classification: heavy jet, large jet, or large turbo prop), feeder fix crossed, and time the aircraft crossed the TMA freeze threshold. Not all scheduled aircraft showed up on all days. We included, nevertheless, all other aircraft in each simulated Noon Balloon, except those aircraft with IDs showing up on a single day only. For this analysis, the lighter traffic that surrounds the Noon Balloon was also included. The separations between one traffic peak and the next were sufficiently long so that all TMA scheduled delays due to one rush could be reduced before the next rush began, and each rush could therefore be independently modeled. For the purpose of this simulation, nominal arrival times at the freeze horizons were chosen as the average of the arrival times of the aircraft with the same ID.

For statistical fast-time analysis the arrival time error distributions at the freeze horizons are also needed. Since, in current operations, no attempt is made by the airlines to control these times, these variations are not related to the aircraft’s capability to meet these times, but they are important in

that they influence gate arrival times. The freeze-horizon arrival variations depend on a variety of random factors. As a reasonable model of these errors, bell-shaped error probability distributions with a range of  $\pm 200$  or  $\pm 400$  sec were chosen for all aircraft. Adding three properly scaled rectangular pseudorandom variables generated the distributions. Fortunately, as will be shown, the average total delays over all aircraft are relatively insensitive with respect to the magnitude of the arrival time errors.

In simulating traffic, one can use either synthetic or actual traffic. When simulating synthetic traffic we have complete freedom in selecting the aircraft mix, the traffic rushes from any direction, and the traffic density. This is useful when one wants to test the traffic management system for a number of conditions. Our early investigations while designing the scheduler were done using synthetic traffic (refs. 1-3). When, however, such a system is to be installed at a given airport, it is best to simulate the existing traffic (refs. 4 and 5). To simulate either type of traffic arriving at an airport, several items need to be known for each arriving aircraft: (1) aircraft ID, to identify the airline and flight number; (2) aircraft type, to determine the separation requirements at the runway threshold for different aircraft types in trail; (3) etaFH, the estimated time when the aircraft will arrive at the freeze horizon arc (a distance equivalent to about 19 min of flying time to the associated feeder fix); (4) feeder fix, the feeder fix that the aircraft will over fly when it enters the TRACON; and (5) random error, the range of the approximately Gaussian distributed time error for the aircraft's arrival at the freeze horizon arc.

We have available two sources of aircraft information. One is represented by the detailed FAA database. The other source is TRAVELPLAN or similar sources, the types of information that travel agents have available. Neither source has directly all the information needed. The detailed FAA database gives statistical data useful for building the traffic model, but it only gives data for all aircraft for the largest U.S. carriers. Also from the tail-number through table lookup, the aircraft types have to be determined. TRAVELPLAN gives the following information for all flights from specified airport A to airport B: (1) aircraft ID, which identifies the airline along with the flight number; (2) airline scheduled gate arrival time; (3) type of aircraft; and (4) airline scheduled flight duration. Items 1 and 3 are directly usable; item 4 can be used to calculate an approximation of arrival error at the freeze horizon. However, what is really needed are the arrival data from *all* airports to the target airport. Both sets of data are needed to construct a valid traffic model. It must be noted that TRAVELPLAN does not directly give all flights from any airport to the target airport. A new search algorithm would have to be added to obtain all the desired data in one search. In contrast, the FAA data base has details for all flights to a selected airport, but only for the largest airlines. Since the aircraft type is missing, one would have to obtain that from a table of tail numbers versus aircraft types, which is available from the FAA. For traffic analysis of a specific airport, one would use most of the data from the detailed FAA database and supply the missing short flights and overseas flights by searching with TRAVELPLAN. This method has been used for collecting 24 hours of arrival time data for DFW, which will be discussed later.

The arrival feeder fix for the aircraft can be determined from the direction of a line between the geometric positions of the departure and arrival airports, and the positions of the feeder fixes at the arrival airport. This would mean that a list of the geometric positions of all U.S. airports must be available, including a program calculating a vector between the departure and arrival airports. (Such data can be found in the Aircraft Owners and Pilots Association (AOPA) Airport Directory).

The time of actual arrival at the freeze horizon (ataFH) is the most difficult one to approximate. From the TMA for each specific type of aircraft, the time interval can be obtained that is required to fly from the freeze horizon to the associated feeder fix, assuming that no delay is required. The minimum time intervals from the feeder fix to each runway touchdown point for different types of aircraft must be determined from radar data during times of sparse traffic. (Note that not all runways are candidates for landing, given the feeder fix). A statistical estimate of the average taxi-in time is obtained from the detailed FAA database. Subtracting the sum of the freeze-horizon-to-feeder-fix time, plus feeder-fix-to-each-runway touchdown time, plus taxi-in time from the gate arrival time, results in an estimate of the arrival time at the freeze horizon ataFH. Here it must be stated that the airlines tend to add additional time to the estimated flight duration, which includes taxi-in time, in order to have a better on-time record and to account for expected delays at the Center.

Random errors still have to be accounted for. For future data analysis the error magnitudes can be roughly estimated from the detailed FAA database on the Internet. For example, we used the data given for the 900 flights from the DFW airline arrival data for a 24-hr day in June 2001. Since the TMA is concerned with touchdown times only, the plot shown in figure 3(a) of interest for simulating arrival traffic where, except for two needed corrections, the time differences between actual and scheduled touchdown times are plotted against scheduled gate-to-gate elapsed time. From actual gate arrival time minus measured taxi time (fig. 3(b)), the actual landing time is obtained. We estimated the taxi-in times as the average over all arrivals which the airline may be using in their scheduling calculations, which is most likely a constant value. We did not correct for another value, the deliberate overestimation of the gate-to-gate travel times, which the airlines make, in order to achieve good on-time records. From figure 3(a), it is possible that elapsed time is overestimated for longer flights. Hence most flights appear to arrive early when plotted versus scheduled elapsed time. For our simulation purposes, we are mostly concerned with the range of errors. (Since we did not record the origins of the flights for the data used in this fast-time simulation, we used a constant error range for the freeze-horizon arrival errors for all aircraft. In addition, unusual events and canceled flights were not modeled.)

For the TMA system in the field, the total delay calculated is transferred to the TRACON up to the maximum delay that each TRACON flightpath can handle (ref. 6). The remaining delay is allotted to the Center. In the example given in this report, the TRACON scheduler is also modeled, since the interaction of the choices of airport acceptance rate (AAR) and the delay distribution function (DDF) parameter dTmax has a large effect on the assigned delays at the Center and the TRACON. In these cases, we also have to estimate the feeder-fix arrival errors. This is another stochastic variable, which will alter the assignments of runways and STAs made in the TRACON from those made in the Center.

The scheduler in the Center's TMA calculates the STA's both to the feeder fixes and to the runways for all aircraft. The scheduling to the runways is necessary in order to ensure that all landing slots at the runway are fully utilized and that the best delay distribution between Center and TRACON is chosen. The details of this are described in reference 3. When the aircraft arrive at the feeder fixes and enter the TRACON airspace, the schedules are updated by the automation tools used in that airspace.

## The Scheduler

**TMA Scheduler Adapted For Fast Time Simulation.** The scheduling algorithms have to meet two sets of constraints: one set consists of the required separations when flying from the freeze horizons to the feeder gates, and another set consists of separations at the runways. As scheduling is done in time rather than distance, the minimum 5 mile in-trail separation is translated to 1-min minimum separation between aircraft separately for each stream class. The different prescribed spatial separations at the runway thresholds as a function of the sequence of aircraft types are also translated into time separations (see table 2). (Small aircraft are rare at DFW.)

**Table 2. Separations including buffer, sec**

1 <sup>st</sup> \ 2 <sup>nd</sup>	Heavy jet	Large jet	Turboprop
Heavy jet	113	135	170
Large jet	89	87	110
Turboprop	83	83	94

For this simulation, the minimum-time separations at the feeder fixes and runway thresholds are assumed to be as discussed above. These were determined from aircraft landing simulations. In the field, time separations are also a function of other factors such as winds, which the real-time scheduler accounts for.

For each traffic sample, the freeze-horizon arrival times for all aircraft are calculated by adding the random freeze-horizon arrival errors to the nominal values, keeping the aircraft in their eight independent streams. (Note that the random component of freeze-horizon arrivals can change the order for the different data samples within a stream class.) Starting with the new estimated time of arrival at a feeder fix (etaff) time ordered aircraft sequences in the same stream class, and beginning with the smallest etaff in each stream, the aircraft are delayed if needed, so that a minimum separation of 60 sec between aircraft is obtained while the order of aircraft in that stream is maintained. The average of the sum of these delays for all traffic samples is the average delay imposed to meet separation constraints in the center.

For all aircraft, we now calculate the runway threshold arrival times to their closest runway under the assumption that there is no other traffic (time from freeze horizon to the feeder fix plus minimum time to the closest runway), and then we order them by estimated arrival times, that is, first-come-first-served. The aircraft with the earliest possible arrival time is now scheduled. Considering table 2, the scheduler tentatively schedules this aircraft to each of the three runways, and then selects the runway that gives the earliest touchdown time. The type of aircraft already scheduled to the specific runway and the type of the tentatively scheduled aircraft determine the minimum separation between them. Therefore, it is not always the path with the shortest time to fly between feeder fix and runway that is chosen. Finally, based on the above criteria, the most recently scheduled aircraft's STA is frozen, and the aircraft is removed from the ordered list of aircraft to schedule. The scheduling process continues with the next aircraft in the queue.

Since, in the TMA, time-control errors at the feeder fix are not being considered, it may be assumed, for simplicity, that all scheduled delays are the total delays. If we did not reschedule at the feeder fixes, this would automatically provide a traffic density at the runway thresholds, which the TRACON controller should be able to handle, especially since the times in table 2 are padded to be sufficiently large. Therefore, at least theoretically, there is no need for an additional airport acceptance rate (AAR) restriction. However, since TRACON management uses it traditionally in order to limit the traffic into TRACON, we simulate this by pushing back aircraft from their estimated feeder-fix arrival time to meet the AAR restriction. This is done as follows. The number of aircraft allowed to enter the TRACON in a 10-min interval is calculated from  $AAR/6$ . For example, at an AAR of 108 aircraft per hour, no more than  $AAR/6 = 18$  aircraft are scheduled in a sliding interval of 10 min, to enter the TRACON. If the AAR constraint is active, it is inevitable that some landing slots are lost.

The comb diagram, figure 4(a), graphically represents the scheduling of a single arrival traffic set; it provides insight into the scheduling process. Each line represents one aircraft. The start of each line specifies the feeder fix, which the aircraft crosses, and the end shows the runway it is directed to by means of computations at the Center. The final, almost horizontal, part of each line, is the minimum distance the aircraft must be from the next aircraft, in order to meet separation standards. Figure 4(b) spells out what is and is not considered a scheduling slot loss. Figures 4(a) and 4(b) point out that slot loss is counted only if the scheduler assigns delay to the aircraft at the end of a gap. The other gaps should be called “traffic gaps,” since they are caused by gaps in the traffic, and, therefore, will be counted separately. In other words, a good scheduler will minimize slot loss, but it cannot prevent traffic gaps in sparse traffic. One can, of course, choose to sum gaps only over portions of a peak traffic interval that may be of special interest and come to various, maybe insightful, conclusions. When sufficient time is available, separating landings above the minimum-time intervals benefit the airlines by reducing delays at the Center, and benefit air-traffic controllers by reducing their workload, provided these separations do not cause subsequent loss in connectivity. The situation would be different, if the traffic density in the TRACON were to be reduced at a cost of extra delay at the Center. TRACON management can do this by reducing the AAR when controllers cannot handle the traffic at the higher rate. We will see the effect on the Center delays when comparing total delays for AAR 108 with AAR 96. The average slot loss over many data samples may tell something about the efficiency of scheduling.

### **TRACON Rescheduling to Minimize $\Delta$ DOC**

The portion of the total delay scheduled for each aircraft by the TMA that is actually taken at the Center depends on the AAR, and on the choice of the  $dT_{max}$  parameter of the Delay Distribution Function, both of which are incorporated in the TMA. The choices must be such that the TRACON, with its limited delay absorption capability, can handle the delay, while considering the safety restrictions imposed by the FAA, and while at the same time minimizing the  $\Delta$ DOC within these restrictions.

Before rescheduling in TRACON, the random feeder-fix arrival time errors are added to the scheduled arrival time. Inside TRACON, based on the actual arrival times at the feeder fixes, a new scheduling process begins, with new delays and new runways assigned. This process begins, just as



in the TMA, with determining the scheduling sequence by first determining the minimum ETA for all aircraft (called eta3), to one of the three runways, then sorting by eta3, and scheduling in that order. Note that the final runway selection is not necessarily the one determined by eta3, but depends on the minimum time the aircraft can be scheduled as a function of the last aircraft already scheduled to each runway.

The newly assigned TRACON delay (and not the one calculated at the Center TMA) is the proper delay to use in calculating the  $\Delta\text{DOC}$ .

From equation (34) of reference 3, we have for the incremental fuel (the fuel increase due to all delays scheduled at the Center [dC] and those scheduled at the TRACON [dT]) as scheduled by TRACON control,

$$F = 2dC + 3dT \text{ (lb)} \quad (1)$$

From equation (35) of reference 3, the incremental direct operating cost, the extra cost due to scheduled delays at the Center and TRACON, is

$$\Delta\text{DOC} = CT (dC + dT) + CF \cdot F \text{ ($) } \quad (2)$$

where CT and CF are the time and fuel cost factors, which, using equation (1) results in the incremental cost

$$\Delta\text{DOC} = dC(CT+2CF) + dT(CT + 3CF) \text{ ($) } \quad (3)$$

In this form of the equation we can explore changes in the cost of time or fuel or both, or even an increase of time spent in TRACON or at the Center. From the figures of reference 3, we determine  $CF = \$0.1/\text{lb}$  of extra fuel and  $CT = \$0.2/\text{sec}$  delay. With the present values of CT and CF,

$$\Delta\text{DOC} = 0.4 dC + 0.5 dT \text{ ($) } \quad (4)$$

This means that flying in TRACON is 25 percent more expensive and that in a single-stage scheduling process, the minimum  $\Delta\text{DOC}$  is achieved by minimizing the TRACON delay, that is, by taking all delays at the Center. As we will see, the result is quite different for the two-stage process, where after Center scheduling, TRACON is completely rescheduled.

As stated in the last section, we have no detailed model of the TRACON traffic control process. Hence, essentially the same scheduling process is used as was used for the Center in order to determine dT. Even though the actual inefficiency of the manual TRACON scheduling procedure is not known, this effect can be explored by multiplying dT by various inefficiency factors “k” greater than 1. The equation then becomes

$$\Delta\text{DOC} = dC(CT+2CF) + kdT(CT + 3CF) \text{ ($) } \quad (5)$$

which means that the aircraft actually spend more time by a factor  $k$  than predicted by our TRACON scheduler model. With this equation and equation (3.2) we can explore different assumptions about the cost, for example, the change in the cost of fuel or time, and the change in efficiency of TRACON scheduling. The terms  $dC$  and  $dT$  are functions of  $dT_{max}$ , the delay distribution parameter. The other values can be assumed constant, while  $dT_{max}$  is varied. Hence, only one run has to be made while varying  $dT_{max}$ , and various assumptions for the other parameters can be explored to study DOCs sensitivity to them. Another method of incorporating an estimate of TRACON scheduling inefficiency was briefly explored, which is assigning larger spaces between aircraft touchdowns in the TRACON simulation than were specified in the TMA calculations.

The  $\Delta DOC$  calculated is the difference in cost when each aircraft could fly without any other traffic (no delay), and with the delays required owing to the presence of other traffic. In reference 4 we explored which  $dT_{max}$  to choose in order to minimize the cost resulting from delays, given different numbers of feeder-fix errors. Here, we are more interested in comparing the costs when choosing slightly different arrival slots at the freeze horizons (to square the traffic peaks) with the cost for the nominal traffic peak. However, we can also compare the effect of feeder-fix arrival errors by first setting those errors to zero and then to the experimentally determined value.

### **Adapting the FTS Scheduler for Other Airports**

Of course, other airports may have different numbers of runways, but this does not change the principle of runway selection. An airport may also have a different number of stream classes, in which case the aircraft will have to be sorted differently. Both changes will be simple to implement. When there is no separate runway available for smaller propeller aircraft, another column and row have to be added to table 2.

### **EARLIER STUDIES USING FAST-TIME SIMULATION**

When there is a gap in the single runway schedule, the aircraft directly following the original gap can speed up by some small amount, and close at least part of the gap. When a number of aircraft following the gap are delayed, all such aircraft will be delayed by a smaller amount equal to the time advance of the initial time-advanced aircraft (see ref. 1). This could have been developed also for multiple runways and studied by means of FTS.

A delay distribution function has been defined which assigns all delay to the TRACON up to a maximum value,  $dT_{max}$ , and the remainder of the delay to the Center. For a single landing runway case and no AAR limits this has been solved for the minimum  $\Delta DOC$  as a function of  $dT_{max}$ , given the feeder-fix crossing errors (see ref. 3). In this report it has been developed for multiple runways and studied by means of FTS.

Sometimes it is preferable to deviate from the FCFS principle in order to have more aircraft land at a preferred runway, which is likely to be the one for which the taxi-in time to the gate is shortest. For this purpose relatively small numbers (between 0 and 60 sec) were added to each STA before

selecting the runway with the smallest value as runway of choice. These numbers were called penalty factors, which were a function of both the feeder fix and the runway. The values chosen by the field-test system engineers were used in the FTS, and the results were as predicted. A few more aircraft landed at the runways of choice at a small cost in average delay increase. However, if all aircraft had been scheduled to the preferred runways, a large average delay increase would have resulted. (In the present report, all penalty factors were set to zero.)

It is shown in reference 1 that when all aircraft are of the same type for a single-runway scheduler, the FCFS scheduler is optimum in terms of minimum mean-squared delays. When aircraft types are mixed, and when more than one runway exists, this is not the case. Using DFW as the model, we developed schedulers which choose for trial scheduling the aircraft with two or three of the smallest etas. Only the simplest one is described here. The scheduler tentatively schedules the aircraft with the lowest etaff A to all three runways. Then it does the same with the aircraft with the next larger etaff B. Then the scheduler schedules either A or B to the runway with the smallest STA. If B is selected in one scheduling cycle, C, the aircraft with the next higher etaff will replace B's position in the scheduling queue, and for the next scheduling cycle aircraft A (not A or B) is scheduled. This is done to prevent some aircraft from being unduly delayed. Compared to the FCFS scheduler, the cost of computing is doubled. When three successive aircraft are considered, the cost of computing goes up by a factor of 18. The reduction of the average delay was about 20 sec for the simplest two-level scheduler and 40 sec for the most complex (three-level) scheduler. This decrease in delay was not considered sufficient for implementation in the field, nor was a formal report published.

In the final two examples, NASA was exploring the possibility of allowing airlines to express relative arrival priorities through development of new sequencing algorithms. Reference 4 introduces a concept of fair delay exchange between two aircraft of the same airline. Reference 5 introduces a method of scheduling a bank of aircraft from the same airline based on preferred order of arrival, rather than on estimated minimum time of arrival at the runway, while the order of arrival of other airlines is not disturbed. This method reduces the arrival order deviation in most cases while causing little or no increase in delays that must be absorbed.

The last two examples were based on the principle of increased cooperation between airlines and the FAA. The example that follows is based on the same principle, and may result in a large payoff for both the airlines and the FAA if it is adopted.

## **PROPOSED NEW USE OF FTS**

That more efficient hub scheduling is an important consideration can be seen from the American Airlines plan to shift a portion of the traffic peaks at DFW to low-density traffic between present peaks, thus increasing the number of traffic peaks, while reducing the arrival rates and associated delays (see ref. 7). Before applying FTS in a new study, it is necessary to look at the present schedule at a hub airport, which does not have assigned landing slots. DFW is a good example, since we have data for DFW's largest traffic peak. However, we will first look at the present 24-hr arrival traffic schedule for DFW. Secondly, since references 4 and 5 show that there is an increased interest in cooperative scheduling between the FAA and the airlines, we will examine Ground Delay

Programs (GDPs), which include several ideas that may be adapted to the present study's investigation of the reduction of delays in normal traffic. It is suggested that the airlines may use a stochastic fast-time simulation (FTS) of the scheduling process as an experimental tool to examine various realizable proposed variations to their fleets' arrival times at the freeze horizons, and to observe the resulting distribution of average delays and altered arrival times of the fleets when airline scheduling and TMA scheduling are considered in tandem.

### **Present Arrival Time Distribution at Hub Airport**

Figures 5(a) and 5(b) represent DFW airline arrival scheduling at the gates for a 24-hr day on 12 June 2001. The data were obtained from the FAA detailed database. Figure 5(a) shows the number of aircraft that are scheduled to arrive at the gates at the same minute. Figure 5(b) shows the resulting number of aircraft scheduled to arrive in each sliding 10-min interval. This is the interval that the TMA uses in order not to exceed the delivery of a given number of aircraft into the TRACON. It is assumed that the present traffic peaks are optimum from the standpoint of the airlines. As can be seen from the AAR limits shown, delays at the Center are thus unavoidable. The question is: Can the traffic characteristic be preserved while reducing delays? Spreading the arrival traffic over a larger time interval will reduce the delays. But what is the cost in connectivity to the airlines? Traffic at hub airports is in banks, which naturally seems to require traffic peaks.

Because we do not have connectivity data for the Noon Balloon, an example for traffic improvement is emphasized here, one that only slightly changes the arrival times and, therefore, should not affect connectivity.

### **Ground Delay Program Insights for Normal Traffic**

Uniform slot spacing is employed generally in all ground-delay programs (GDPs), which contributes to their success (refs. 6, 8-10). Therefore, it is reasonable to assume that delays can be substantially reduced by similar methods in normal traffic (traffic not subjected to GDP). This is accomplished by scheduling uniformly spaced traffic slots at the entry to the freeze horizons in order to convert the sharply pointed traffic peaks into somewhat wider rectangles; we will call this the squared version of the traffic peaks. Moreover, in GDPs several mechanisms are used to assign these slots in an attempt to be fair to all airlines; some of these GDP techniques may be adapted for normal traffic. The overall process is called collaborative decision-making (CDM), and the initial part is called ration-by-schedule (RBS).

To visualize how RBS may apply to normal scheduling, assume that the initial airline gate arrival schedule is as shown in figure 5 with many traffic peaks. Often more than one aircraft is initially scheduled at the same time and aircraft of several airlines are mixed. First, for all aircraft, the arrival times at the freeze horizons must be estimated from the scheduled gate arrival times. The individual estimates depend on the type of aircraft and on the specific freeze horizon with its associated feeder fix. The calculated freeze-horizon arrival times will also have multiple aircraft assigned to the same time. Second, around each traffic peak, new scheduled times of arrival at the freeze horizons are assigned (slots) that are spaced at equal intervals, regardless of the freeze horizon at which an

aircraft arrives. The number and separations of the slots are determined by the AAR that the airport can handle. (For the purpose of equal spacing one must assign slots in fractions of a minute. It is, of course, understood that arrival errors will blur these distinctions.)

By including some of the original low-density traffic skirts around the traffic peak, each newly scheduled squared traffic peak is now a rectangle. The squared traffic peak must not fill the total time interval between adjacent peaks. Following each traffic peak, there must be a period of low airline-scheduled density traffic. This period serves as a buffer for random errors of the arrival traffic, and it should be large enough to permit the spreading caused by increased delays caused by occasional small reductions of TRACON-commanded AAR without interfering with the next traffic peak.

The slots are initially assigned by airline, not by aircraft, in a first-come-first-served order, according to the original scheduled arrival times at the freeze horizons. When there are more airlines involved with the same original freeze-horizon arrival time, a method needs to be found to assign the slots fairly to the airlines. For instance, when there are five aircraft originally assigned to the same freeze-horizon arrival time, and only one is not from the dominant airline, the center slot is assigned to the aircraft that is not from the dominant airline.

Once the RBS is completed, the airlines are free to assign specific aircraft to the slots, which, considering the airlines' constraints and needs for connectivity, will result in optimal traffic for them (a problem each airline must solve for itself). The above process, in contrast to GDP, is a static one or at least a slowly varying process, which only changes as traffic schedules are changed.

As part of GDP, mediated bartering is considered. That is, airlines can offer a slot in trade for one of a range of preferred slots, which another airline may wish to accept. Rules for canceled or delayed flights are given for GDPs. These rules will be different in the static process, where it is possible that an airline actually would prefer that a certain aircraft arrive later than at the initially assigned slot. Here one can envision that several airlines propose slot-trade offers, and a computer program sorts out all possible matches. If the original schedule was close to optimum, as assumed, slot trading should be minimal.

In GDP this is followed by a compression procedure, which fills slots with aircraft of the same airline, when flights have been canceled. In normal traffic, compression may not be needed, especially if at the beginning of each traffic peak slots are reduced in width to produce some airborne delay, which permits the airport to be well utilized even when errors and cancellations occur. The TMA will then fulfill the function of compression, and it will reassign aircraft to enter the TRACON according to the actual dynamic situation of arrivals near the feeder fixes.

## **RESULTS FOR EXAMPLE PROBLEM**

### **Scheduled Delays With and Without Slot Assignment**

We believe that it is sufficient to analyze one traffic peak in detail to show the principle of delay reduction by slight rescheduling. The Noon Balloon at the DFW airport, for which detailed data are

available, is used. In this section, only the TMA scheduling is considered, as it calculates schedules and the delays to touchdown and then backs up its calculations to the feeder fixes. The resulting schedules are discussed as if air-traffic control could execute the plan as presented without separate Center and TRACON areas of control.

From the field data, figure 6(a) shows the average times the aircraft crossed the freeze threshold in numerical order of their arrival times. The slope of straight line A is an approximation of the reciprocal of the maximum arrival rate for a portion of the arriving aircraft. For  $n = 18$  to  $n = 72$  this results in an average separation of aircraft of 33 sec or 109 aircraft/hour, which is just above what TRACON can handle. Hence the assigned delays at the Center tend to increase during this time interval, especially if TRACON reduces the AAR to a value of 96. Curve B in figure 6(a) suggests an equal spaced distribution of airline scheduled arrival times between  $n = 2$  and  $n = 78$ , and, therefore, indirectly, of freeze-horizon arrival times, which results in an average separation of 40.5 sec or 88 aircraft/hour arriving at any one of the feeder fixes. Figure 6(b) shows the actual separations between arrival times at the feeder fixes between  $n = 2$  and  $n = 78$ , for the error-free schedule; the separations show relatively large variations. TRACON could handle this arrival rate, if the rate remained relatively steady. Thus, equally spaced arrival slots should result in lower delays, in spite of arrival errors. Thus, by spreading the originally scheduled traffic uniformly according to curve B in figure 6(a), the sparse traffic is condensed just before and just after the traffic peak, and the traffic in the central part of the peak is spread out.

In figures 7(a) and 7(b), we compare comb diagrams of an example of the nominal schedule with that of a squared schedule. It is not important to follow individual aircraft schedules. Primarily, it can be seen that compressing the scheduled arrival times in the early and late parts of the traffic peak makes the individual delays smaller in figure 7(b) than in 7(a). In addition to lower total delay, there are more traffic gaps in figure 7(b) than in 7(a), which makes it easier to compensate for guidance errors which naturally will occur. As we will see, this also results in a minimum change in airline schedules while benefiting both the airlines and ATC. Curve C in figure 6(a) is given as a nonpractical extreme example of delay reduction, which would have an adverse effect on connectivity. We are now looking statistically at changes that are caused by squaring of the Noon Balloon traffic peak.

The resulting average delays and etaff changes from squaring the originally scheduled traffic are shown in figure 8. Figure 8(a) shows how much the scheduled arrival times at the feeder fixes and the freeze horizon have to be changed from the original set to achieve the resulting average delays shown in figure 8(b). The results were obtained using the approximately Gaussian-distributed time error at the freeze horizon of  $\pm 400$  sec. The new etaff (nominal freeze-horizon arrival times–19-min) are constant values. But as was the case with the original schedules, each of the etaff for the 1,000 Noon Balloon samples was disturbed by the same uncertainty as for the original schedule. Figure 8(b) shows the delay distributions plotted against new etaff's for three different squared peaks and for the original etaff for the nominal traffic peak. Equally spacing time slots from  $n = 18$  to  $n = 78$  is still above airport capacity, and the delay slowly increases for later arrivals. This is along the straight line A in figure 6(a), which almost follows the time versus position curve. For the preferred airline schedule ( $n_1 = 2$  to  $n_2 = 78$ ) compared with the original schedule, the early aircraft have to be scheduled closer together with a maximum change of 6 min, and later the aircraft have to be spread out slightly.

The benefit of equally spreading the arrival times is clearly seen in figure 8(b) by comparing the original delay curve with the preferred one. For the preferred rescheduling, beginning with  $n = 2$  for the next 12 aircraft, the new TMA scheduled arrival time is advanced up to almost 6 min. This advance slowly changes to a delay of little over 4 min, and at the 78th aircraft the schedule change goes to zero. For the case of extreme delay reduction ( $n_1 = 2$ ,  $n_2 = 100$ , curve C in fig. 6(a)), the arrival times would have to be changed by a large amount, making acceptable connectivity unlikely.

Several performance histograms, comparing the original data with the preferred one, is discussed next. Figure 9 shows the average delay histograms for the 1,000 Noon Balloon samples (for the original and the preferred airline schedules) for the original schedule, and for the equally spaced slots between  $n_1 = 2$  and  $n_2 = 78$ . The effect of the accuracy of meeting the assigned slots was determined, but the data have not been plotted. It was noted, however, that there is a relatively small advantage in average delay reduction when the slot assignments are achieved more accurately, that is,  $\pm 100$  sec instead of  $\pm 400$  sec (not plotted for clarity of the figures). Figure 9(b) shows the same data for a reduced AAR of 96 aircraft per hour, which was the case at DFW in IFR conditions. Here the advantage of spreading the freeze-zone arrival times is even more obvious. Another way to summarize and compare the data is shown in a histogram (fig. 10) of the number of different data samples with different average delay intervals for the 1,000 Noon Balloon data samples. Again, it is seen that for both AARs the uniformly spread arrival times reduce the delays substantially, and that increasing the arrival errors at the freeze horizon causes a relatively small increase in average errors.

Figure 11 shows the average of the means and standard deviations for different amounts of stretching for two AARs. As pointed out earlier, stretching beyond  $n_2 = 78$  is likely to cause connectivity problems.

Subtle changes of a system responding to random events can often mask the improvement of a single event. This is demonstrated in figure 12. The accumulation of square symbols represents the comparison of delays between equally spaced etas  $n_1 = 2$  and  $n_2 = 78$  or 88. The wider the separation of aircraft schedules, in general, the lower the average delay. However, because of random freeze-horizon arrival errors, for a certain number of cases with otherwise identical noise, the average delays for specific data samples were larger for the wider-spread airline's scheduled arrival times. These are the points above the  $45^\circ$  line in figure 12. As a second example, the cluster of circles represents the comparison of delays for individual traffic samples between the original scheduling and preferred scheduling ( $n_1 = 2$  and  $n_2 = 78$ ). Here it is clear that the delay reduction is very robust, and that equally spreading the times is always an advantage, provided, of course, that connectivity is not violated.

In order to study several other situations, we made other runs while providing minimum outputs. Forty-eight runs were made of 1,000 traffic samples—each to explore the performance of the different aspects and methods of airline scheduling in interaction with the TMA scheduler (see table 3, page 17). For comparison of the results, we used the same starting pseudorandom number for all tests. At this number of samples, the starting value of the pseudorandom number generator made negligible difference in the outcome of the tests (not shown). In addition, all the tests shown in table 3 were run with a smaller arrival-error range of 200 sec. This change made very little difference in the outcomes, although the average Center delay was usually a few seconds smaller for the narrower error range.

The first 18 tests are concerned with all three runways in operation. In lines 1 and 2 of table 3, the response of the TMA to original traffic is compared for the two typical TRACON-commanded arrival rates. For the larger AAR = 108, the average Center delay is almost reduced to half, and the variations between samples (sigma) are substantially reduced with increased AAR, as is the slot loss. The same tendency is true for all cases when the traffic is spread more evenly. The question is how often does TRACON have to reduce its AAR when going from VFR to IFR? Although the simulation does not prove this, it is likely that when the traffic is spread more uniformly, TRACON can handle the traffic more easily, thus making an improved assignment of arrival times even more desirable.

Two methods of traffic-slot assignments were investigated: (1) choose equal separation when the traffic begins to get dense and increase the traffic density somewhat when originally it is light (rows 3 to 10, table 3), or (2) in addition, increase the traffic density when the traffic is light before the beginning of the traffic peak and after it is light again (rows 11 to 18), so that we have an increased initial and final arrival rate when compared with the original traffic. This is compensated for by a lower, more uniform arrival rate during the time of the original peak traffic. The second method is more advantageous to the airlines as was discussed in detail in the last section. In both cases the slot loss decreases as the average traffic becomes less dense and the gaps increase.

We also investigated original scheduling and scheduling with assigned slots when only two runways are operating (rows 19 to 36, table 3). Of course, the TMA scheduled delays will increase drastically, but the evenly spaced scheduling from  $n = 2$  to  $n = 78$  still shows a definite advantage over the original schedule. Compressing the early, widely spaced arrivals reduces the delays in the second case. This is similar but more effective than the time advance explored in reference 1. From the last column of table 3 (max\_sta), it can be seen that the last scheduled aircraft ( $n = 111$ ) is never delayed, which means that delays between traffic peaks are still independent. This was not the case when an attempt was made to schedule the traffic to a single runway.

Comparing the six sets of three rows each (rows 19 to 36, table 3), which are concerned with only two runways in operation, it is noted that the order of the Center delay magnitudes remain the same for any combination of the active runways. Also, for conditions that are otherwise the same, the delays do not change very much as a function of the active runways. Too low a choice of AAR triples the total delays. But, increasing the AAR past 96 has no effect on the outcomes. This happens because at that point the airport's two runways are fully utilized; that is, all aircraft on both runways are separated by their specified minimum time interval.

Various other pieces of information are given concerning the various gaps in the schedule. For all cases, when three runways are used, the slot-loss decreases with increased spread ( $n_1 - n_2$ ) and it decreases with increased AAR. This is true also for the case of two runways in use, although here it would not be useful to reduce the AAR to a lower value.

### **Interaction Between Center and TRACON Scheduling**

The interactions between the parameters AAR and the delay distribution  $dT_{max}$  on the overall scheduling results are somewhat complicated. So simpler examples will be discussed first.



**Table 3. Statistical results**

AAR	n1	n2	type	Rny1-3			tot_del	sigma	sep_del	slot_ls	intel_gap	opn_spc	max_sta	COMMENTS
96	0	0	1	1	1	1	202.7	170.9	9.9	1846	7476	9322	8258	nominal traffic all 3 runways active
108	0	0	1	1	1	1	114.5	103.3	9.9	724	8619	9343	8258	
96	18	78	3	1	1	1	142.0	113.5	9.0	1811	7511	9322	8258	stretched traffic beginning at start of traffic peak all 3 runways active
96	18	88	3	1	1	1	112.6	85.7	9.4	1769	7554	9323	8258	
96	18	98	3	1	1	1	25.7	12.0	6.8	280	9076	9356	8258	
96	18	104	3	1	1	1	19.7	8.2	5.6	36	10004	10040	8258	
108	18	78	3	1	1	1	68.0	47.4	9.0	693	8648	9341	8258	
108	18	88	3	1	1	1	52.2	31.9	9.4	612	8731	9343	8258	stretched traffic beginning before start of traffic peak all 3 runways active
108	18	98	3	1	1	1	23.7	10.8	6.8	12	9344	9356	8258	
108	18	104	3	1	1	1	19.5	8.0	5.6	1	10039	10040	8258	
96	2	78	3	1	1	1	60.5	37.0	8.1	1517	8266	9783	8258	
96	2	88	3	1	1	1	50.9	29.2	8.4	1354	8423	9777	8258	
96	2	98	3	1	1	1	22.6	9.7	6.6	122	9607	9729	8258	stretched traffic beginning before start of traffic peak all 3 runways active
96	2	104	3	1	1	1	18.5	6.9	5.5	6	10349	10355	8258	
108	2	78	3	1	1	1	33.8	18.1	8.1	255	9538	9793	8258	
108	2	88	3	1	1	1	31.7	16.4	8.4	196	9589	9785	8258	
108	2	98	3	1	1	1	21.9	9.4	6.6	3	9726	9729	8258	
108	2	104	3	1	1	1	18.5	6.9	5.5	0	10355	10355	8258	nominal traffic 2 active runways various AARs
64	0	0	1	0	1	1	1232.9	837.7	9.9	3671	946	4617	8304	
64	0	0	1	1	0	1	1214.3	823.6	9.9	3735	462	4197	8301	
64	0	0	1	1	1	0	1246.3	843.0	9.9	3752	822	4574	8370	
96	0	0	1	0	1	1	470.1	366.7	9.9	0	4529	4529	8277	
96	0	0	1	1	0	1	475.5	356.5	9.9	5	4035	4039	8258	stretched traffic 2 active runways n = 2 - 78 various AARs
96	0	0	1	1	1	0	480.1	369.5	9.9	9	4428	4436	8339	
108	0	0	1	0	1	1	470.1	366.7	9.9	0	4529	4529	8277	
108	0	0	1	1	0	1	474.5	355.9	9.9	0	4039	4039	8258	
108	0	0	1	1	1	0	477.7	368.2	9.9	0	4436	4436	8339	
64	2	78	3	0	1	1	1049.3	685.5	8.1	3765	849	4614	8277	stretched traffic 2 active runways n = 2 - 78 various AARs
64	2	78	3	1	0	1	1051.3	681.9	8.1	3783	652	4435	8259	
64	2	78	3	1	1	0	1083.0	699.7	8.1	3826	712	4538	8339	
96	2	78	3	0	1	1	260.2	182.1	8.1	0	4612	4612	8277	
96	2	78	3	1	0	1	300.7	193.4	8.1	13	4416	4429	8258	
96	2	78	3	1	1	0	301.1	202.9	8.1	23	4513	4536	8339	stretched traffic 2 active runways n = 2 - 78 various AARs
108	2	78	3	0	1	1	260.2	182.1	8.1	0	4612	4612	8277	
108	2	78	3	1	0	1	298.5	192.2	8.1	0	4429	4430	8258	
108	2	78	3	1	1	0	296.0	200.0	8.1	1	4536	4537	8339	

smpls = 1000 number of noon balloon samples smpls = 1000 is large enough for larger number to have little effect on results  
 rnd1 = 1995 starting number of pseudo random number generator. Number has little effect on results for smpls = 1000  
 arr-err = 800 sec range of random arrival errors (approximately Gaussian mean = 0; range = +/- 0.5 arr\_err) From field data.  
 AAR Airport arrival rate determined by TRACON control  
 n1 first aircraft in the etaff series evenly spread  
 n2 last aircraft in the series evenly spread  
 type 1 = use nominal feeder fix arrival times  
 3 = use evenly spread arrival times n1 to n2  
 Rny1-3 1 = runway operating; 0 = runway not in operation  
 tot\_del Average total delay/aircraft (sec)  
 sigma standard deviation of the average total delays  
 sep\_del average delay per aircraft to achieve minimum in trail separation  
 slot\_ls total gaps where the aircraft going to the same runway has scheduled delay  
 intel\_gap total gaps where the aircraft going to the same runway has no scheduled delay  
 opn\_spc sum of slot\_ls and intel\_gap  
 max\_sta average maximum sta for the traffic peak

NOTE: These three parameters were kept constant for the results shown in this table.

To tie in with reference 3, data were used from the first 54 aircraft in our Noon Balloon data sample (type of aircraft, feeder fix, and aircraft ID), but the etaFH was assigned randomly through a range of 90 min. This is a runway acceptance rate of 36 aircraft per hour. Sorting by etaFH constituted a new data set. To generate traffic samples using this data set, we then added to each aircraft a bell-

shaped uncertainty to the freeze-horizon arrival times with zero mean and 800-sec range. In addition, a  $\pm 180$ -sec feeder-fix arrival error was assumed, it too with a bell-shaped distribution. (This differs from the example in ref. 3, where each sample was generated by randomly assigning 54 aircraft through the 90-min range.)

To study the efficiency of the multiple runway scheduler, it was of interest also to simulate two or three times the number of aircraft, as well as runways during the same time interval of 90 min. As shown in figure 13, changing the feeder-fix arrival errors from a range of  $\pm 180$  sec to 0 gave a relatively small percentage improvement of  $\Delta\text{DOC}$ , which was largest for small  $dT_{\text{max}}$ . The single-runway curve for the nominal feeder-fix arrival errors in figure 13 has a minimum at  $dT_{\text{max}}$  of 180. The two runway curves have a weak minimum at  $dT_{\text{max}} = 270$ , and the three runway curves flatten out to a constant value at high  $dT_{\text{max}}$ , when all delays are taken in TRACON. Of more interest is the difference between the one-, two-, and three-runway minimum  $\Delta\text{DOC}$ 's. The optimization of the runway selection has reduced the  $\Delta\text{DOC}$ 's considerably for more runways, even though the original traffic density per runway was the same.

In the remainder of this section, the Noon Balloon is studied and compared with its squared version. Because of the small effect on the results, there is only mild concern with improvements obtained when the feeder-fix arrival error is reduced. Fortunately, in understanding the scheduling processes and the results, it is not necessary to be immediately concerned with the  $\Delta\text{DOC}$ -results. Once the outcomes of various strategies have been computed in terms of the actual scheduled delays in Center and TRACON while using the fast-time simulation, the various  $\Delta\text{DOC}$ 's can be computed in one step by applying the different forms of the  $\Delta\text{DOC}$  equations.

To understand the somewhat unexpected outcomes, the original Noon Balloon scheduling is first examined when the traffic is not AAR-limited (see fig. 14(a) for various  $dT_{\text{max}}$ ). Definitions for the parameters in figure 14 and table 4 appear in the box following table 4. From the view of the Center scheduler, which originally schedules to the runway, the Delay Distribution Function divides the total delay for each aircraft in such a manner that the average total delay is a certain constant value independent of  $dT_{\text{max}}$  ( $\Delta\mu C + \text{TDC} = \text{constant}$  (not shown)), which makes the resulting scheduled touchdown times for each aircraft independent of  $dT_{\text{max}}$ . As a function of increasing  $dT_{\text{max}}$ , the average TMA scheduled Center delay ( $\Delta\mu C$ ) always decreases from a maximum value to zero, and the TMA scheduled TRACON delay does the reverse (TDC).

We will demonstrate this by means of comb diagrams at a later time. Similarly, as a function of increasing  $dT_{\text{max}}$ , the TRACON delay computed inside TRACON (TD) always increases from a minimum value (greater than zero) to a maximum constant value, after the delays for all traffic samples have been transferred to the TRACON. The three delays  $\Delta\mu C + \text{TD}$ , TD, and TDC all converge to constant values, once all delays are taken in the TRACON. From then on, the Center delay remains zero except for  $fhD$  and  $fferrD$ , the delays that need to be imposed to meet the in-trail separations at the freeze horizons and the feeder fixes, and these are small. These statements are true, independent of other parameters such as AAR or the type of airline schedule used. Figure 14(a) shows the curve for TD with the feeder-fix arrival error  $\pm 3$ -min in order to compare it with TD0, the curve for no such error. The differences are small, and this curve is omitted from further graphs of this kind. Figure 14(b) for the squared Noon Balloon looks similar to 14(a), but there are two prominent differences: the TDC at large  $dT_{\text{max}}$  is about one-half of that in figure 14(a), and  $dT_{\text{max}}$  at which all delay is absorbed in the TRACON is also much smaller.

**Table 4. TRACON has same minimum separations as Center**

AAR	Typ	dTmax	$\Delta\mu C + TD$	$\Delta\mu C$	TDC	TD	$\Delta DOC$	$\Delta DOC_{ctr}$
300	1	0	155	99	0	56	74	47
300	1	420	63	0	99	63	39	57
300	3	0	90	48	0	42	46	25
300	3	210	43	0	48	42	27	30
108	1	0	205	157	0	48	94	70
108	1	540	65	0	157	65	40	86
108	3	0	94	53	0	42	48	27
108	3	210	42	0	53	42	27	33
96	1	0	297	256	0	41	129	109
96	1	690	66	0	256	66	40	135
96	3	0	126	86	0	40	60	40
96	3	300	43	0	86	43	27	49

Definitions for table 4 and figure 14

average	average means the average per aircraft over all aircraft in our noon balloon data sample, where random errors were added to arrival times at the freeze horizons
AAR	airport acceptance rate (set by TRACON). The number of aircraft TMA will schedule to enter the TRACON airspace in a 10-minute sliding interval is AAR/6
Typ	nominal = 1 vs. equal = 3 spacing of scheduled freeze horizon arrival times
dTmax	portion of the total delay (Center plus TRACON) as computed in the Center TMA that is completely assigned to the TRACON; the remainder is assigned to the Center
$\Delta\mu C + TD$	actual average total delay assigned by the TMA ( $\Delta\mu C$ ) and FAST (TD)
$\Delta\mu C$	additional average delay assigned to the Center by the TMA
TDC	average TRACON delay assigned by the Center TMA
TD	average TRACON delay scheduled by the TRACON scheduler (FAST) with $\pm 3$ minute feeder fix arrival errors
TD0	same as TD but without feeder fix arrival errors
$\Delta DOC$	direct operating cost (additional average cost per aircraft due to TMA commanded average delays $\Delta\mu C + TD$ )
$\Delta DOC_{ctr}$	Center portion of average direct operating cost
fhD	average delay due to freeze horizon arrival errors imposed by the TMA to meet the intrail separations at the freeze horizons
fferrD	average delay due to feeder fix arrival errors to meet the intrail separations at the feeder fixes

Since the equivalent figures to figure 14 all have the same character, the data are presented in table 4, where  $\text{Typ} = 0$  is for the nominal and  $\text{Typ} = 3$  for the squared Noon Balloon, and  $\Delta\text{DOC}_{\text{ctr}}$  is the  $\Delta\text{DOC}$  calculated for single-step scheduling based on the Center TMA data only. It can be seen for  $dT_{\text{max}} > 0$ , that the lower the AAR, the higher must be  $dT_{\text{max}}$  for a given type of scheduling to accommodate all delays in the TRACON. For each particular AAR and type,  $\Delta\text{DOC}$  is always smallest for the large  $dT_{\text{max}}$ . The smallest  $\Delta\text{DOC}_{\text{ctr}}$  is the one for  $dT_{\text{max}} = 0$ , since less fuel is used when the aircraft spends more time in the Center.

To gain a better insight into the behavior of the curves shown in figure 14, somewhat simplified comb diagrams are studied for one specific traffic sample at the extreme values of  $dT_{\text{max}}$  (0 and 450). Figures 15(a) and 15(b) show the diagrams from the view of the Center scheduling, where all delays are either at the Center or in the TRACON. We can see that the scheduled STAs are identical for both figures. However, the STAff values that the TRACON scheduler has to deal with are smaller in the case of large  $dT_{\text{max}}$ . Hence, we can expect smaller TRACON scheduled touchdown times for the latter case. This is shown in figures 16(a) and 16(b). The individual changes are relatively small, hence the delay changes are also plotted for individual aircraft in figure 17. Finally, a comparison is made between total delays ( $\Delta\mu\text{C} + \text{TD}$ ) of 100 samples with identical initial conditions but with the extreme  $dT_{\text{max}}$ 's. In addition, figure 18 shows the comparison for an intermediate  $dT_{\text{max}} = 150$ . There is an overlap between Noon Balloon samples at  $dT_{\text{max}} 150$  and 480, but more often than not the results for larger  $dT_{\text{max}}$  show lower delays. It can be seen from figure 18 that individual traffic samples have quite a range of average total delays, and that  $dT_{\text{max}} = 480$  compared to  $dT_{\text{max}} = 0$  always has the lowest delay for identical incoming traffic.

It may be of interest to know what the reassignment of runways accomplishes, given whatever the ATAff's are (eta3 order versus etaff order). The results are shown in figure 19. The figure shows that the scheduling in eta3 order is advantageous for all values of  $dT_{\text{max}}$ . We have also tested removing just the eta3 ordering for the Center scheduler, or for both Center and TRACON schedulers. The results are shown in figure 19. The lowest  $\Delta\text{DOC}$  always occurs when both runway optimizers are active.

Since, ordinarily, we have feeder-fix arrival errors, and the TRACON scheduler reschedules each aircraft, including a new runway selection, the new total delay, the sum of the Center and the scheduled delays inside TRACON ( $\Delta\mu\text{C} + \text{TD}$ ), does not remain constant, but starts with a value for low  $dT_{\text{max}}$  considerably higher than the total delay computed from the Center perspective ( $\Delta\mu\text{C} + \text{TDC}$ ).

Center delay is defined here as the sum of the actual delay in the Center ( $d_c$ ), plus the arrival errors at the freeze horizon ( $fhD$ ), and the arrival errors at the feeder fixes ( $fferrD$ ):

$$dC = d_c + fhD + fferrD \text{ (sec)} \quad (6)$$

For convenience, equation (3) on page 9 is repeated here:

$$\Delta\text{DOC} = dC(\text{CT} + 2\text{CF}) + kdT(\text{CT} + 3\text{CF}) \text{ ($) } \quad (3)$$

These two equations show that decreasing variable  $dC$  and increasing variable  $dT$  with  $dT_{\max}$  multiplied by different constants results in a constant  $\Delta DOC$  for large  $dT_{\max}$ . In all cases examined,  $\Delta DOC$  initially decreases with increasing  $dT_{\max}$ . Hence, there are two possibilities: the first minimum value occurs before all delay is transferred to the TRACON or at the point where all delay is absorbed in the TRACON airspace.

Figures 20(a) and 20(b) are for  $AAR = 300$ , with feeder-fix arrival errors. The resulting  $DOC$  is studied for different assumptions to indicate the sensitivity to different economical changes:

1. Nominal  $\Delta DOC$  including costs to compensate for freeze-horizon and feeder-fix arrival errors
2. Doubling the fuel cost
3. Calculating the  $\Delta DOC$  as seen by the TMA

Just as in the single-runway case (similar to reference 3), there exists a weak minimum  $\Delta DOC$  before all delays (except for the delays that must be taken in the Center to meet the separation requirements at the freeze horizons and at the feeder fixes), are assigned to the TRACON only in the case where the cost inside TRACON being quadrupled led from the nominal ( $k = 4$  in eq. (3), curve not shown in fig. 20). For the squared Noon Balloon and realistic feeder-fix arrival errors, we again have to wait for the plateau, when all possible delays are assigned to the TRACON, to minimize the differential cost. Comparing the figures for both nominal the Noon Balloon and the squared version, figures 20(a) and 20(b), it is seen that substantial reductions occur in  $\Delta DOC$ s for the squared Noon Balloon over the nominal version. Figures 20(a) and 20(b) show plots of the  $\Delta DOC$  for the single-step case in which all possible delays are calculated in the Center. For these cases, cost is smallest at  $dT_{\max} = 0$ , and increases as more time is spent in TRACON.

Table 4 already recorded the effect of limiting traffic flow into the TRACON by means of the AAR. In all cases the  $\Delta DOC$  and minimal total delays occurred when all possible scheduled delays were transferred to the TRACON. This gave the somewhat surprising result that the highest average delay for the smallest AAR was obtained for both the nominal and the squared Noon Balloon. However, when the optimal total delays and  $\Delta DOC$ s were compared for the combined system, which reassigns runways and recalculates  $\Delta DOC$ s after feeder-fix crossing, they are only weakly dependent on the AAR, provided that  $dT_{\max}$  is chosen so that all delays are assigned to the TRACON. It is also noted that the required  $dT_{\max}$  is much smaller for the squared version of the traffic peak than for the nominal version. To further understand this, figures 21(a) and 21(b) show the histograms for the nominal and squared Noon Balloon of individual aircraft delays for 1,000 data samples ( $1,000 \times 111$  aircraft/sample = 111,000 aircraft) for the individual delays for all three AAR. As can be seen, there is very little difference between the results for the AAR. The original peaks of 43,000 and 53,000 aircraft with small delays is mostly a result of the initial peak traffic followed by sparse traffic in the time interval we studied. Comparison of figures 21(a) and 21(b) shows the advantage of squaring the Noon Balloon traffic.

## CONCLUDING REMARKS

We have shown that fast-time simulation (FTS) has certain benefits and requirements:

1. One of the keys to a valid FTS is to build a computer model of the system that is to be studied. In the case of the TMA, many details such as aircraft dynamics and weather models had to be omitted. This means that we cannot make any experiments involving these variables. To build a useful model, it is important to work closely with the system designers.
2. With FTS we explored system performances over a range of initial conditions, as well as random disturbances, since we had the proper models for these variables from field tests. Such tests would be difficult using full-scale, real-time simulations of the TMA.
3. Graphical representations, as well as intermediate printouts of the results, were very important in checking results. For instance, the comb diagram was very helpful in spotting errors in the code, as was the printout of runway balancing.
4. Another aspect of the FTS model, which is a simplification of the real TMA, is that it must not be used beyond the capability of the actual system. For example, in the FTS model, we treated all aircraft information as one sequence that could be manipulated as a whole. In actual traffic, aircraft appear sequentially, and scheduling has to be performed on partial sequences. Thus an investigation such as described in the section titled Earlier Studies of Fast-Time Simulation would be valid. Another method of reducing delays consists of going through the scheduling process several times, each time using the last results as a start, and stopping when the next iteration gave a higher delay. This would be a nonvalid use of the FTS simulation for the above reasons.
5. An advantage of FTS of the TMA was that no deep knowledge of statistics was required. One can simply run enough samples until the output is essentially independent of the sample size.
6. FTS had a large payoff in terms of useful insight acquired and in the speed with which it was obtained.
7. Since some of the fine details of the actual system have not been implemented, the results are only an approximation of the actual TMA performance.
8. Theoretically it is, of course, possible to use the complete TMA program and to automate the manned simulation by replacing the pseudopilots and controllers with simulations, and then to run the system with computer-generated traffic samples in faster than real time. Except for the difficulties of writing programs that simulate the situational awareness of controllers, and the resulting controller commands to meet the scheduled arrival times, as well as simulating controller, pilot, and aircraft interactions, this would be another approach for checking out the complete TMA program and its performance before installing it at an airport.

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4. Carr, G. C.; Erzberger, H.; and Neuman, F.: Delay Exchanges in Arrival Sequencing and Scheduling. J. Aircraft, vol. 36, no. 5, Sept./Oct. 1999.
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(Available from <http://www.isr.umd.edu/NEXTOR/pubs/WP-01-3.pdf>)





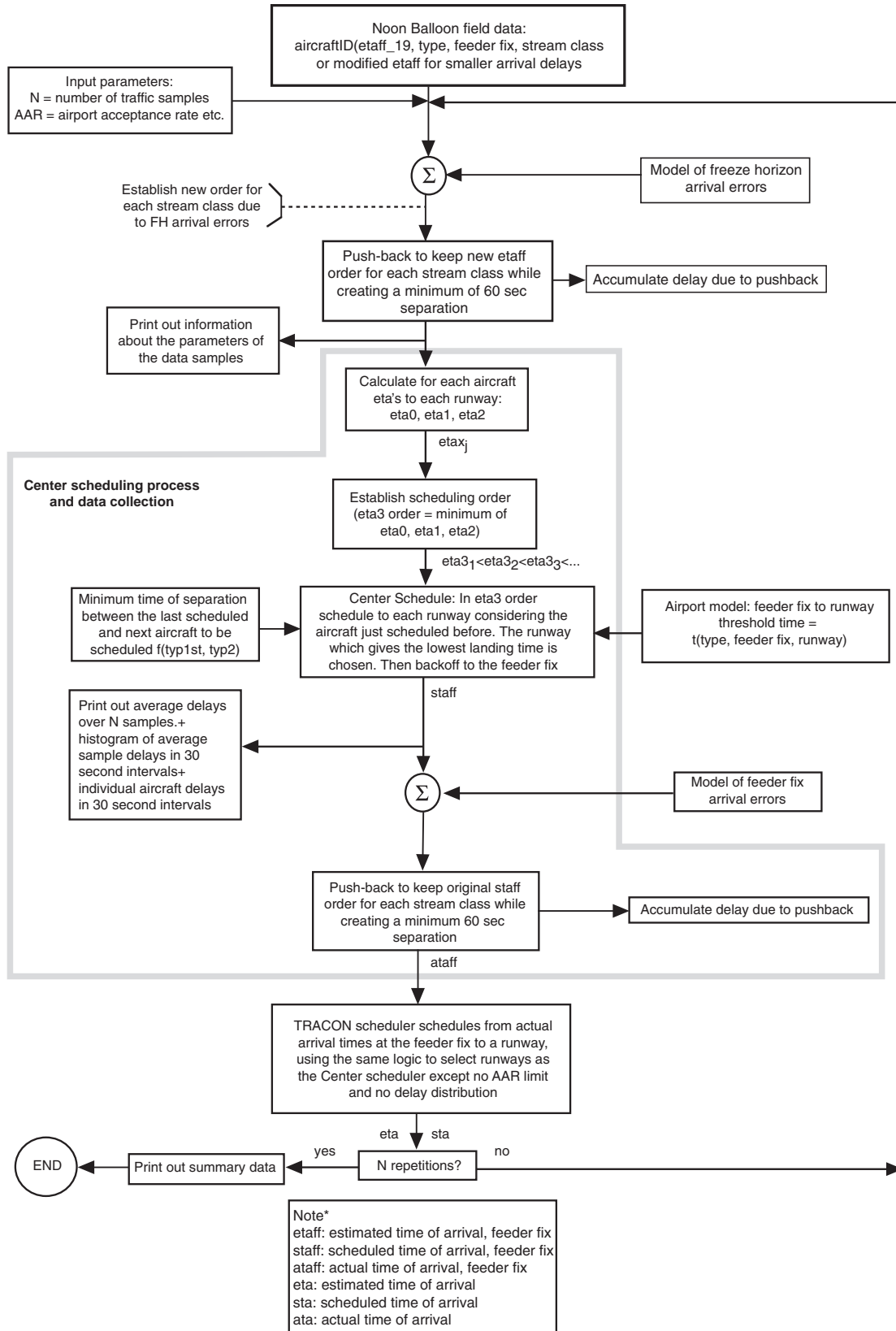
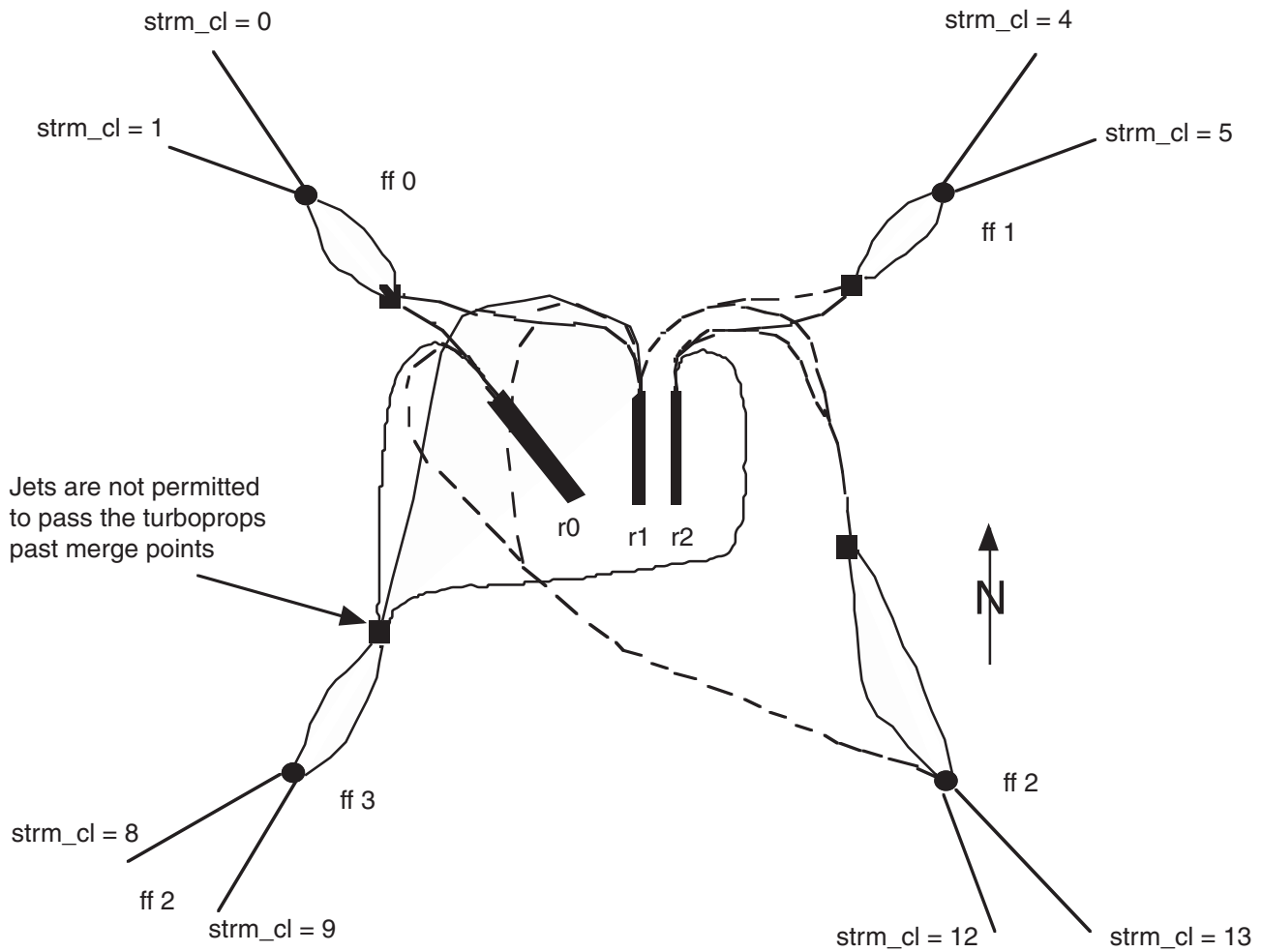
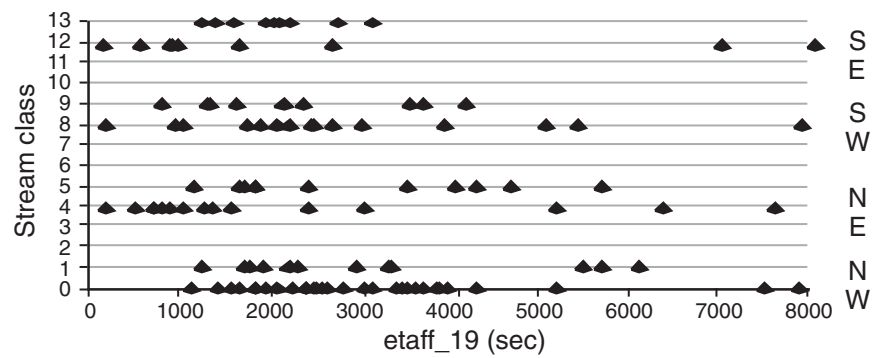


Figure 1. Fast-time estimated arrival-time error distribution.



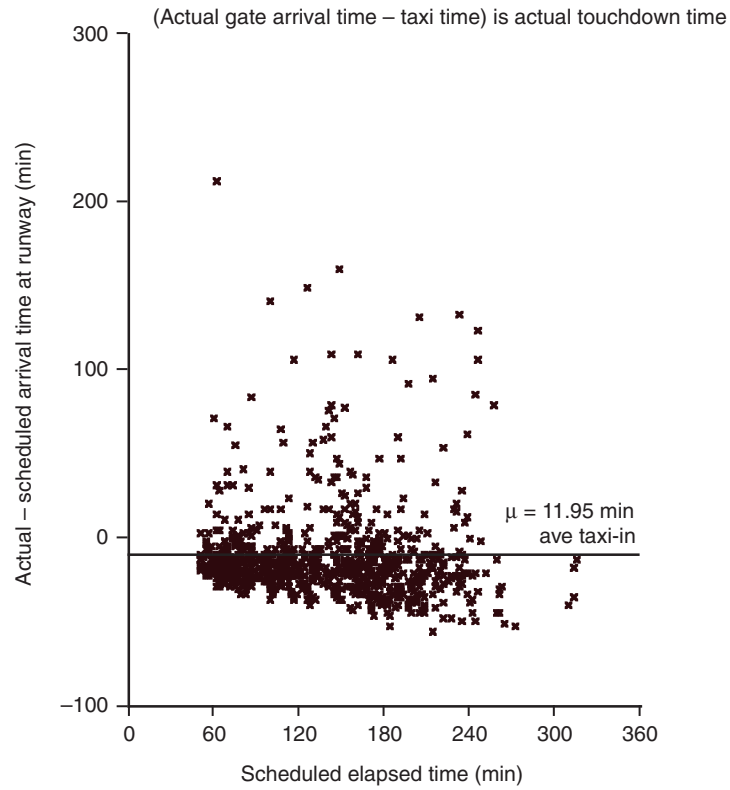
(a) DFW runways and minimum-time flightpaths as of 1996.



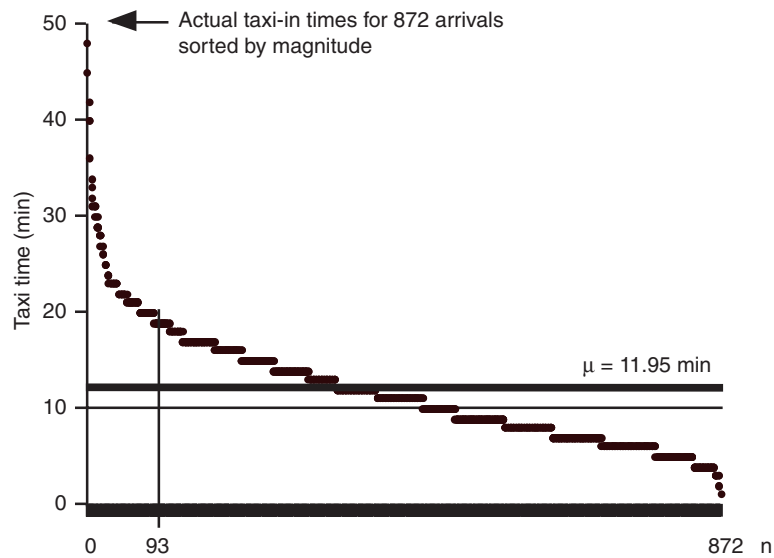
Even-numbered stream classes are jet routes  
 Odd-numbered stream classes are jet prop routes

(b) Traffic crossing the freeze horizons.

Figure 2. DFW Noon Balloon traffic and flightpaths.

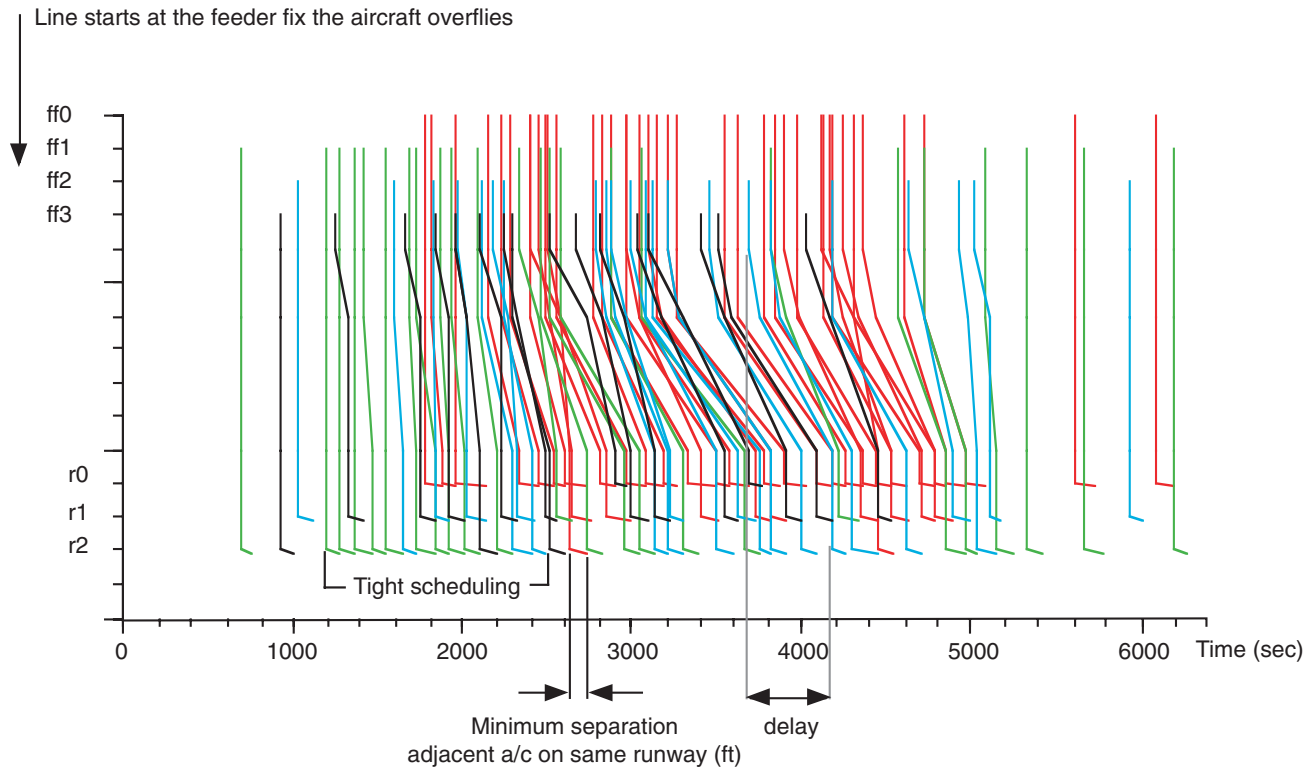


(a) Runway arrival errors 24 hr DFW June 2001.

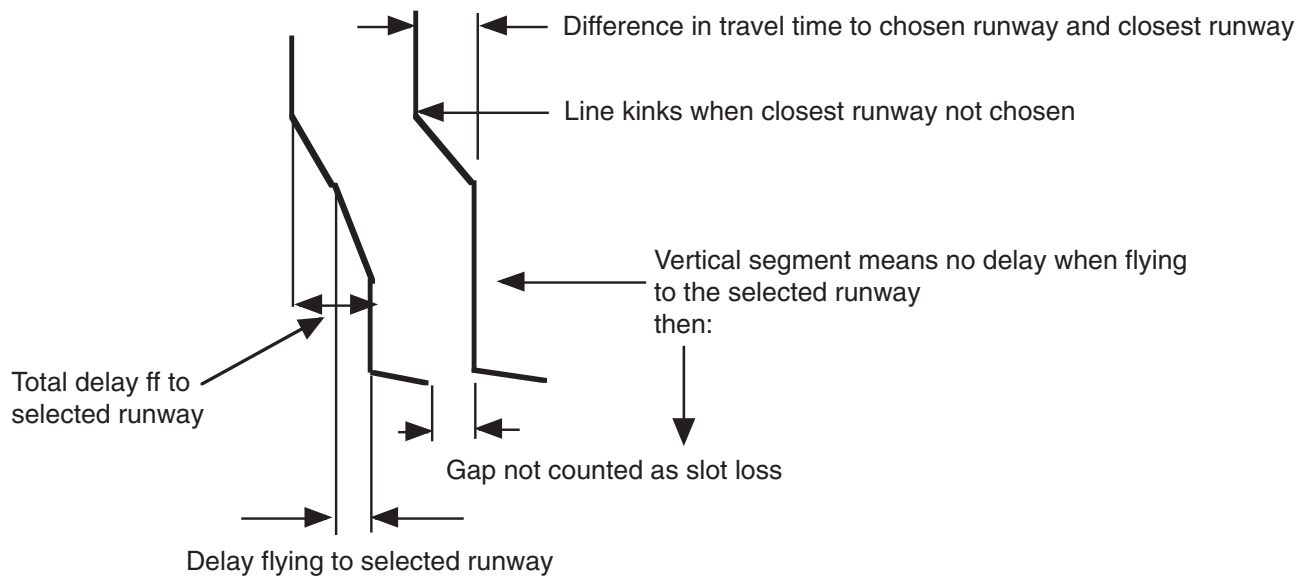


(b) Taxi-in times DFW 24 hr DFW June 2001.

Figure 3. Some statistical data from the detailed FAA database.

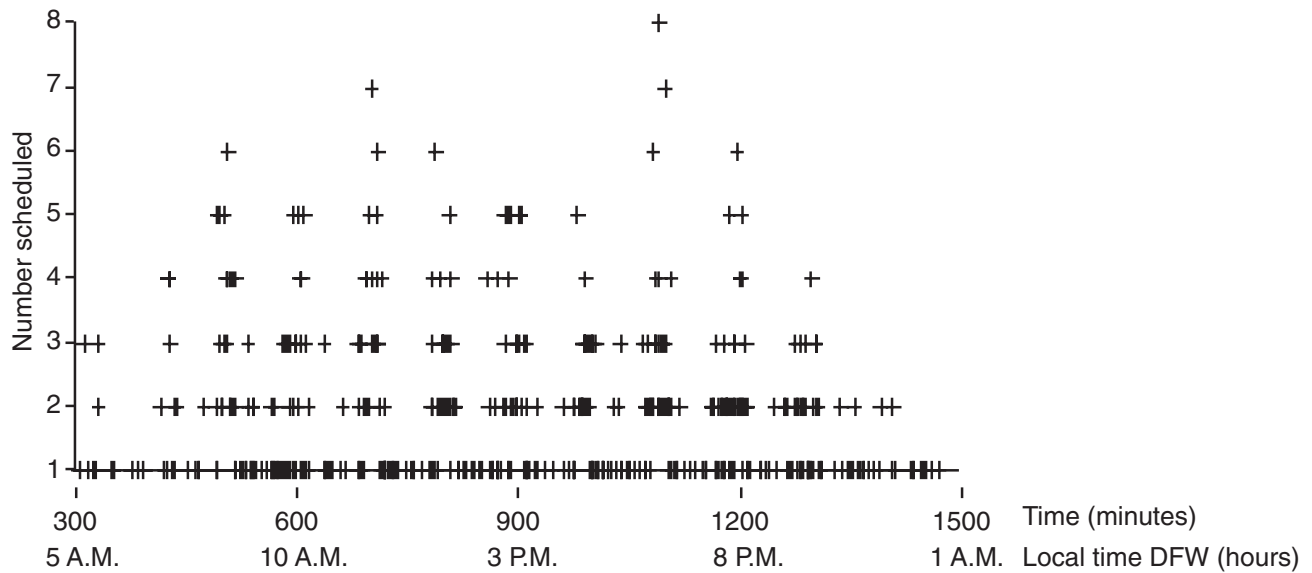


(a) Comb diagram of Noon Balloon sample.

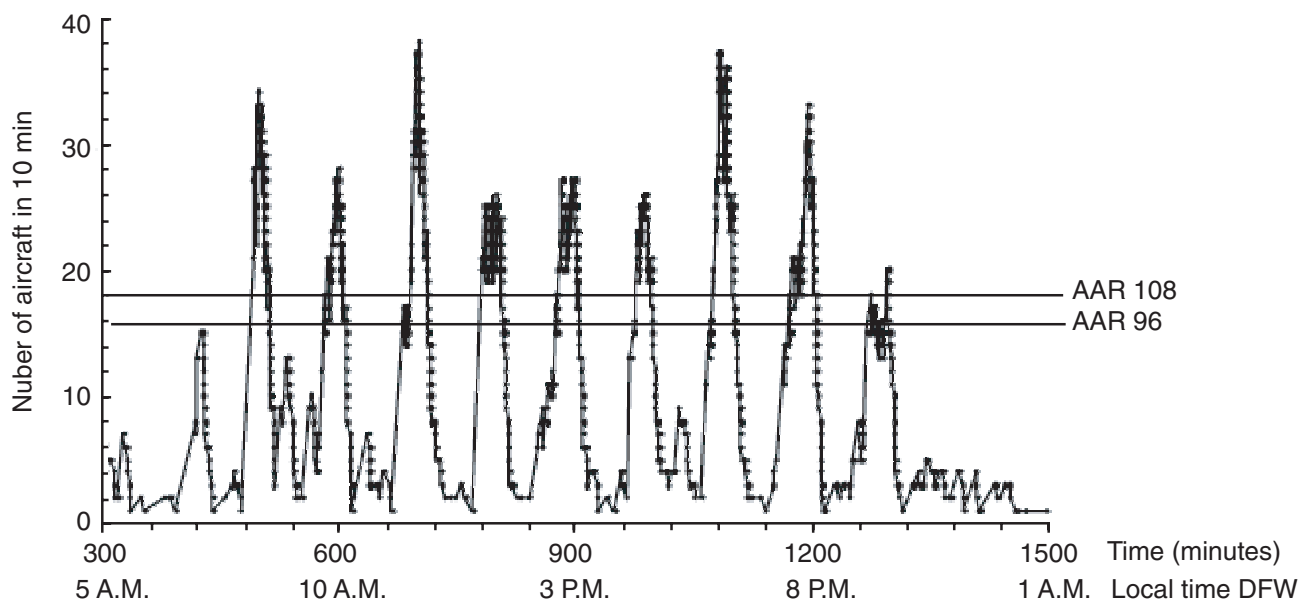


(b) Detailed description of logical content of figure 4(a).

Figure 4. The comb diagram and detailed explanation of its elements.

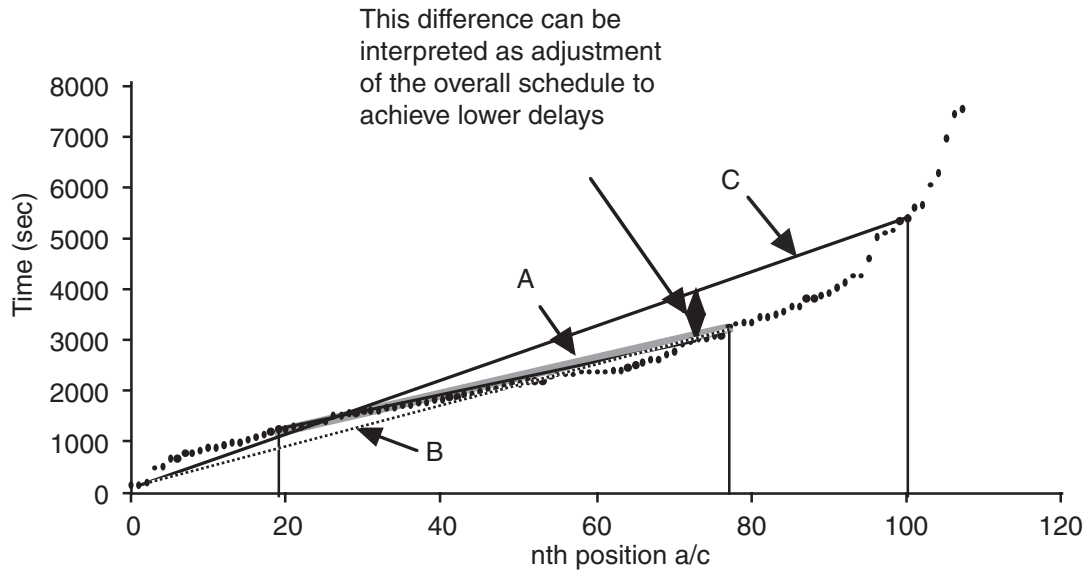


(a) Number of aircraft scheduled to arrive at the same minute versus time.

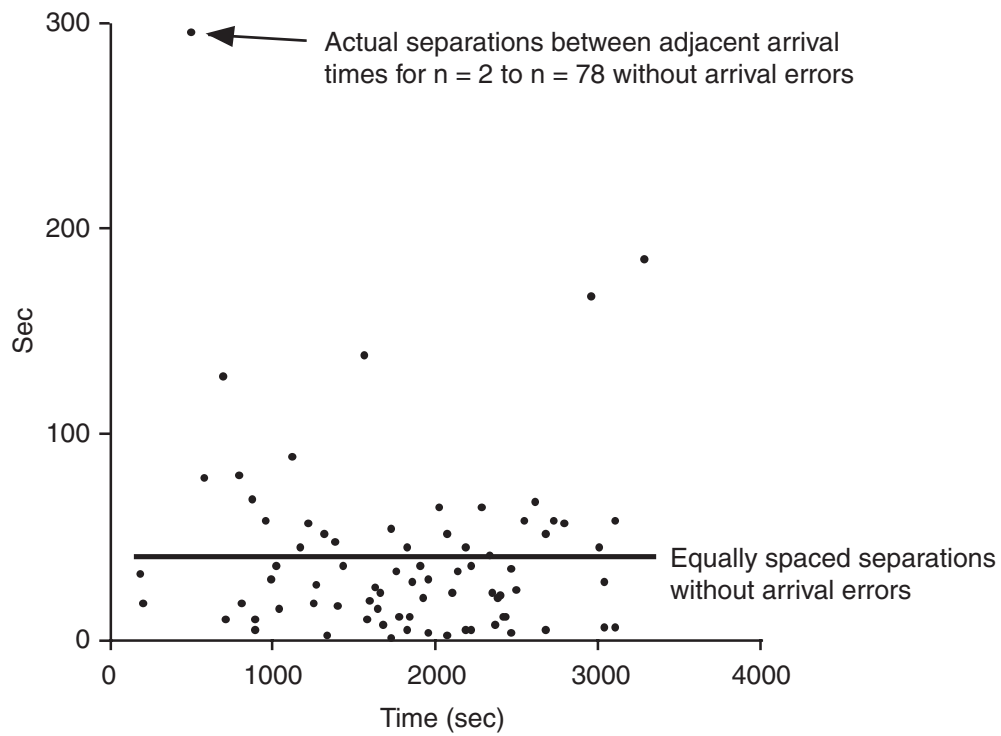


(b) Number of aircraft scheduled to arrive at DFW in sliding 10-min intervals as of 12 June, 2001.

Figure 5. Two representations of aircraft scheduling density at DFW on 12 June 2001.

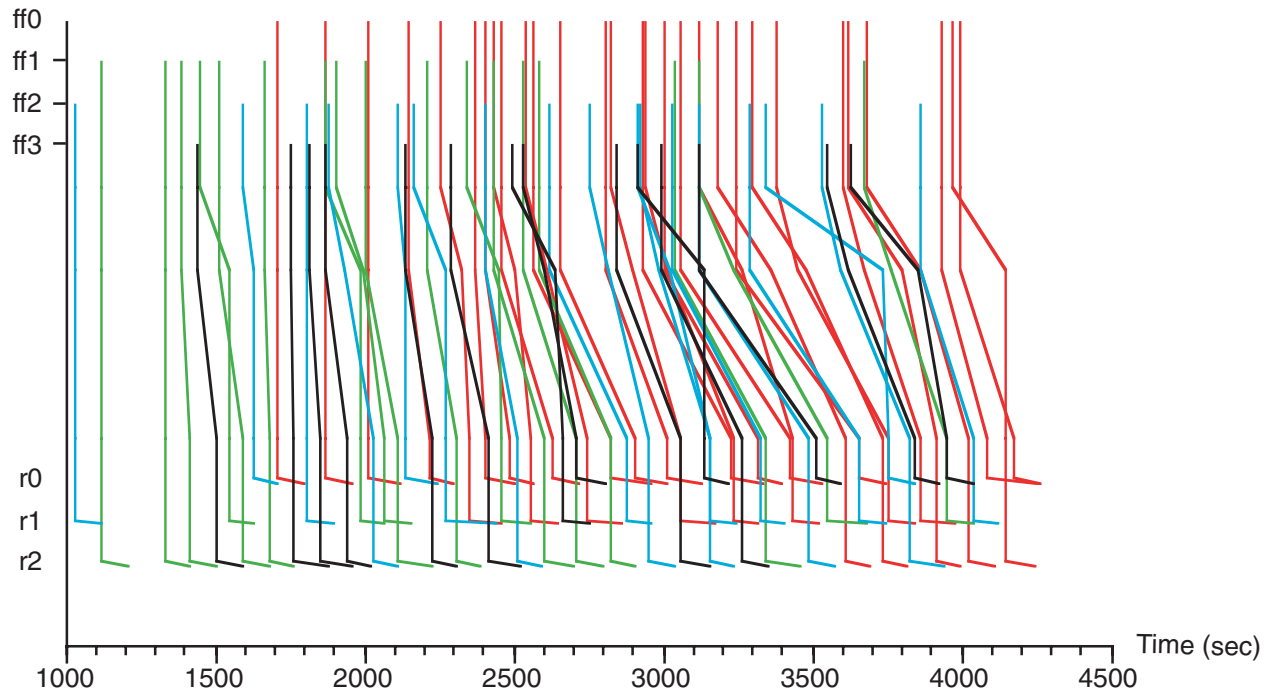


(a) Arrival times at the freeze horizons versus positions in the Noon Balloon sequence.

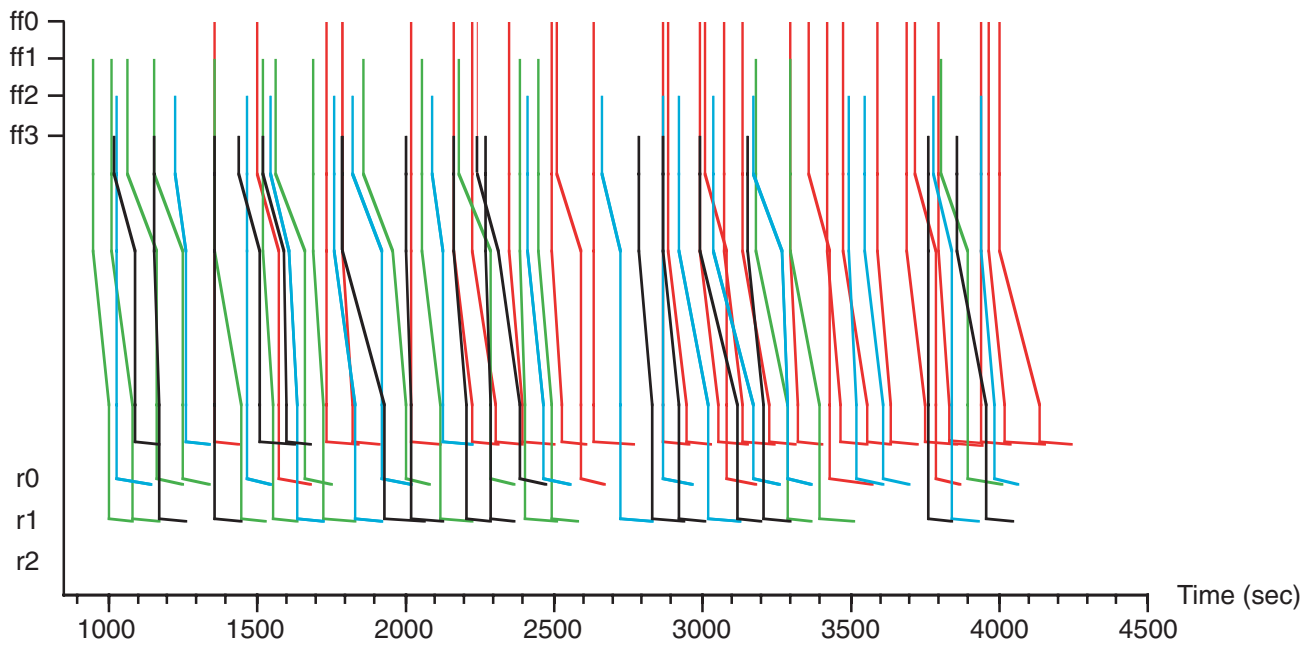


(b) Comparing the nominal spacing with equal separation spacing at the freeze-horizon arcs when no arrival errors have been added.

Figure 6. Different representations of the Noon Balloon arrival data at the freeze horizons.

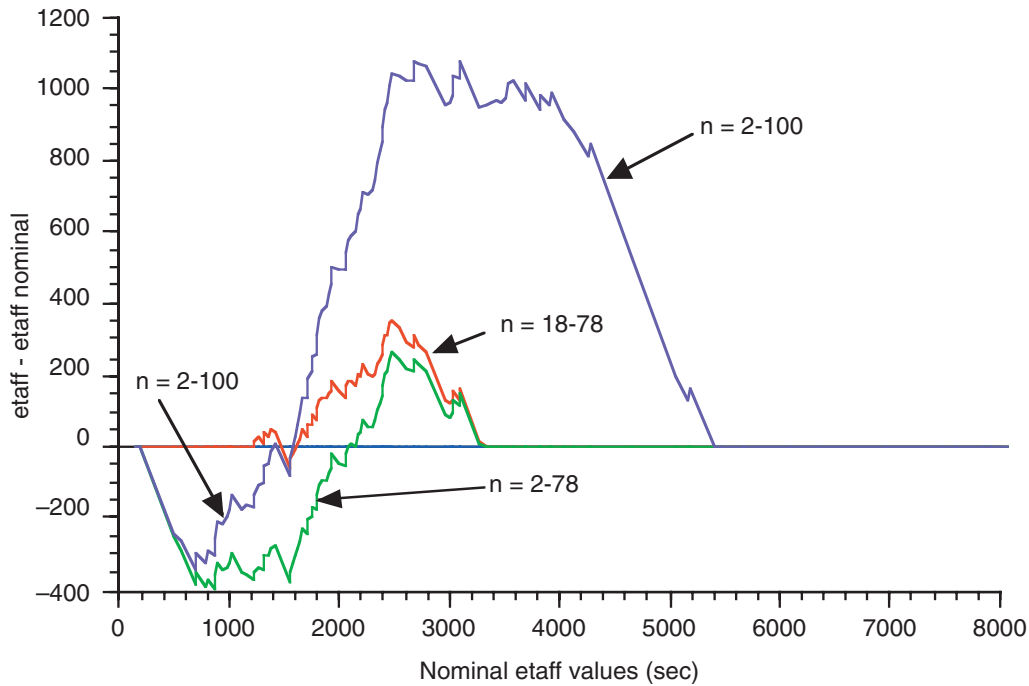


(a) Nominal traffic only  $n = 2$  to  $78$  shown.

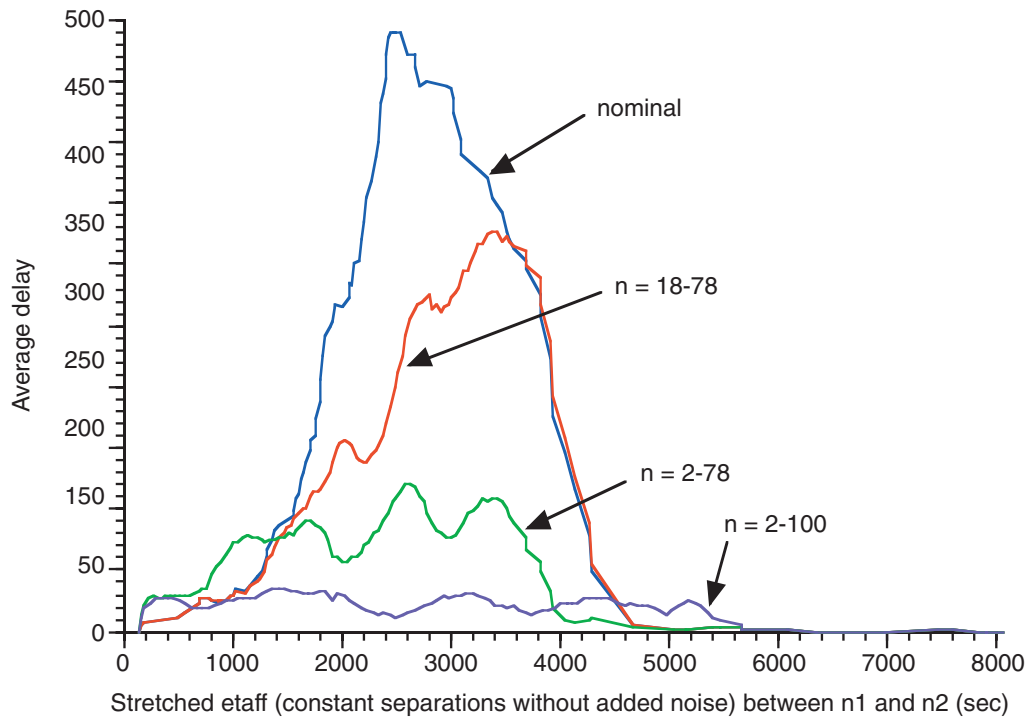


(b)  $n = 2$  to  $78$  equally spread only  $n = 2$  to  $78$  shown.

Figure 7. Comparison of samples of nominal scheduled traffic and equally spaced traffic including arrival errors.



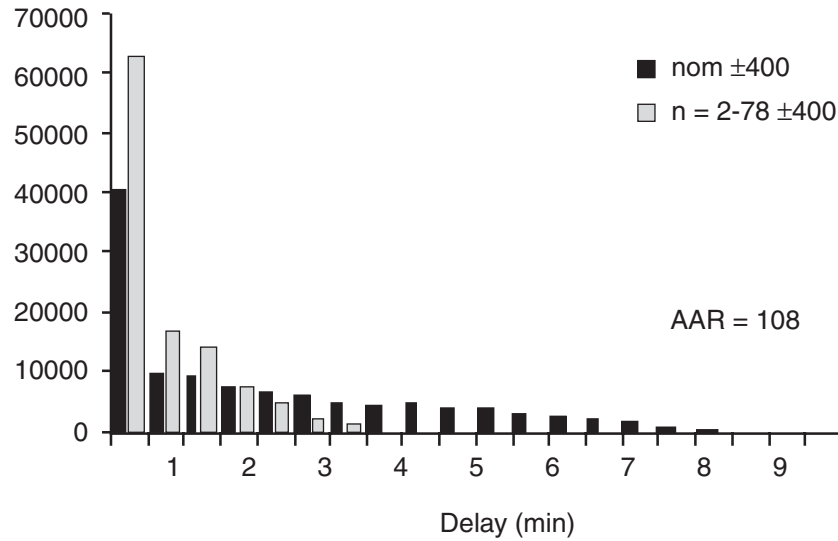
(a) Change in scheduled arrival times from the original values as calculated in the Center.



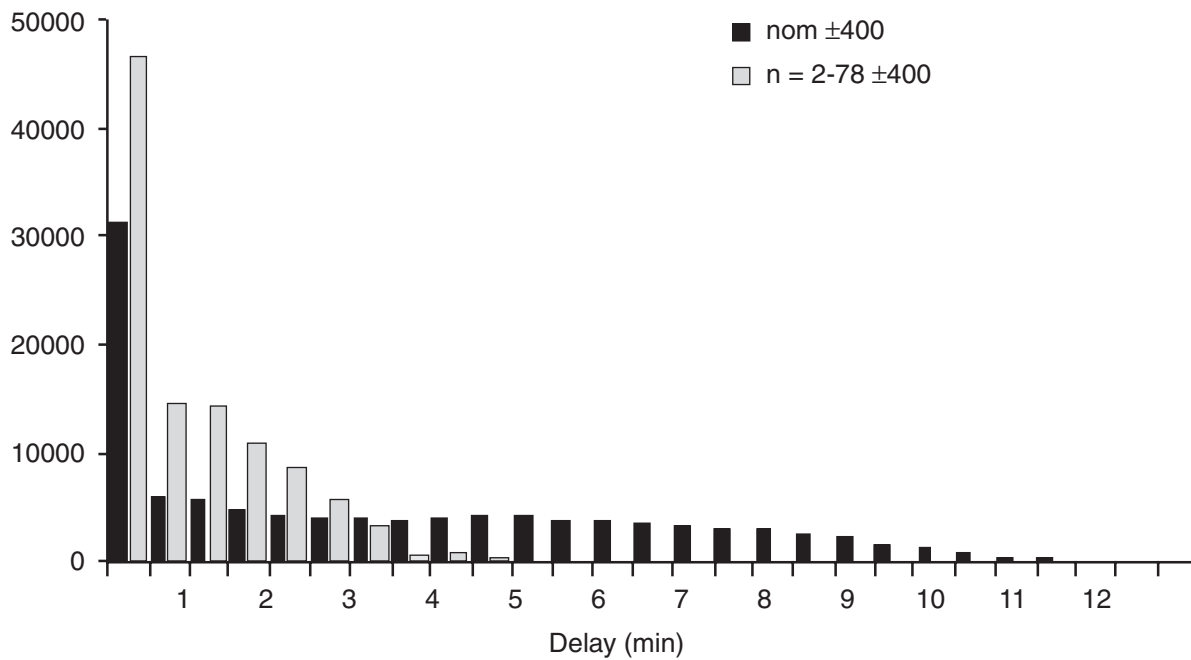
8(b) Average total delay distribution for different airline schedules as calculated in the Center.

Figure 8. Arrival time changes from nominal schedules and resulting average delays when equally spaced schedules are applied over a range n1-n2, while the rest of the traffic remains nominal.



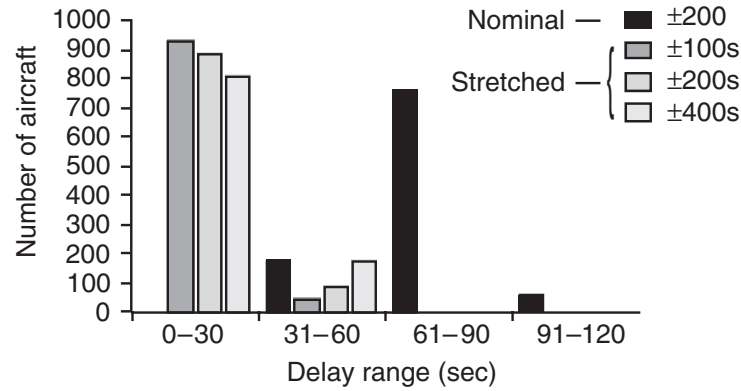


(a) Histogram of individual scheduled delays AAR = 108 in 30 sec-intervals.

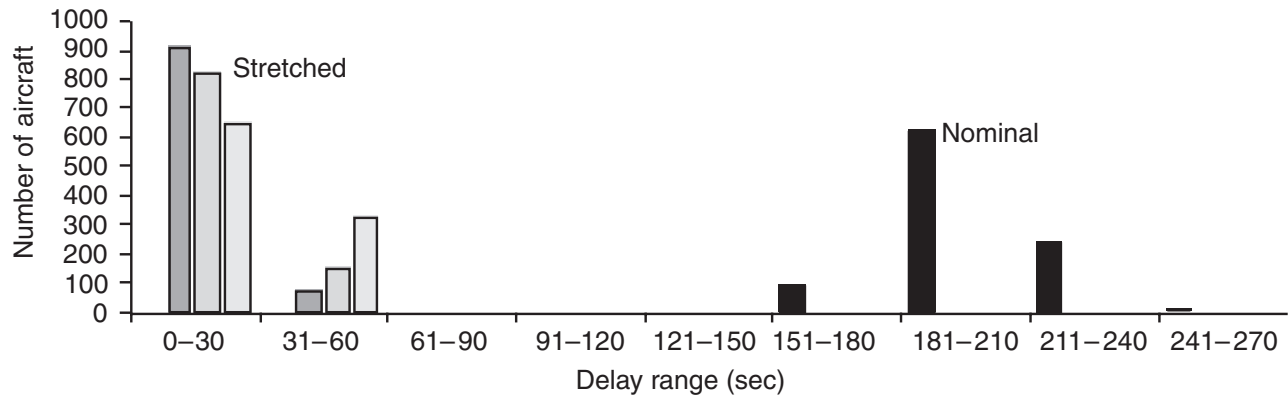


(b) Histogram of individual scheduled delays AAR = 96 in 30 sec-intervals.

Figure 9. Comparing nominal and preferred spread schedules for two different AARs. (Note: Both nominal and spread schedules perform slightly better when the freeze-horizon errors are set to  $\pm 100$  sec instead of  $\pm 400$  sec as shown in the above figs.)



(a) Number of aircraft samples with different accuracies of meeting the assigned slot or 1,000 Noon Balloon samples AAR = 108 aircraft per hour.



(b) Number of aircraft samples with different accuracies of meeting the assigned slot times for 1,000 Noon Balloon samples AAR = 86 aircraft per hour.

Figure 10. Studying the effect of different aircraft arrival accuracies for two AARs.

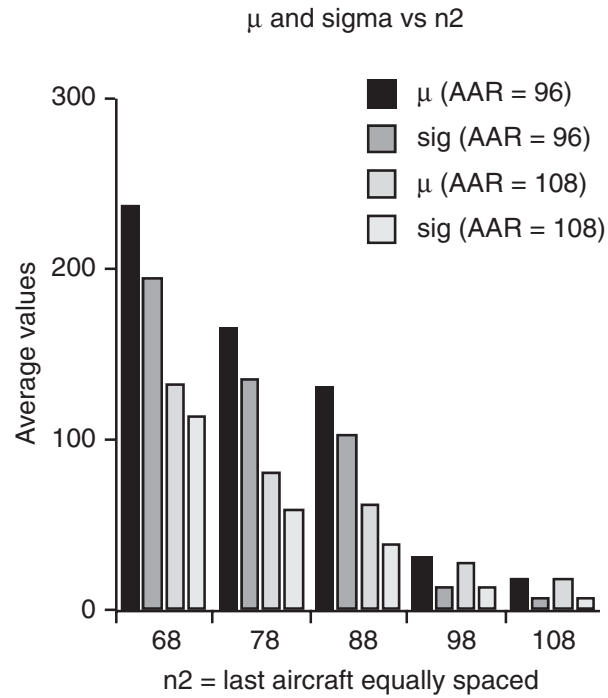


Figure 11. Mean and sigma delays for two typical AARs, 96 and 108 for equally spaced scheduled aircraft between  $n_1$  and  $n_2$  in the Noon Balloon nominal eta ordered sequence (eta not corrupted by arrival errors at the freeze horizon) where  $n_1 = 18$  for all examples.

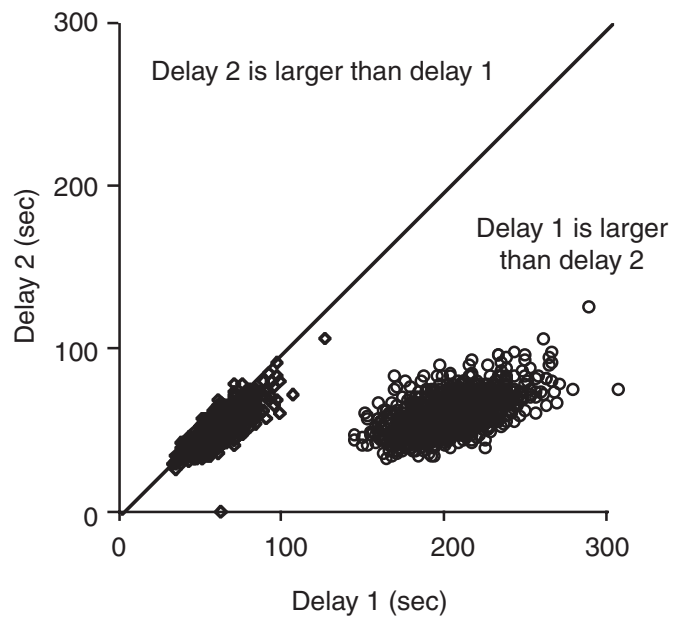


Figure 12. Comparison of delays for two methods.

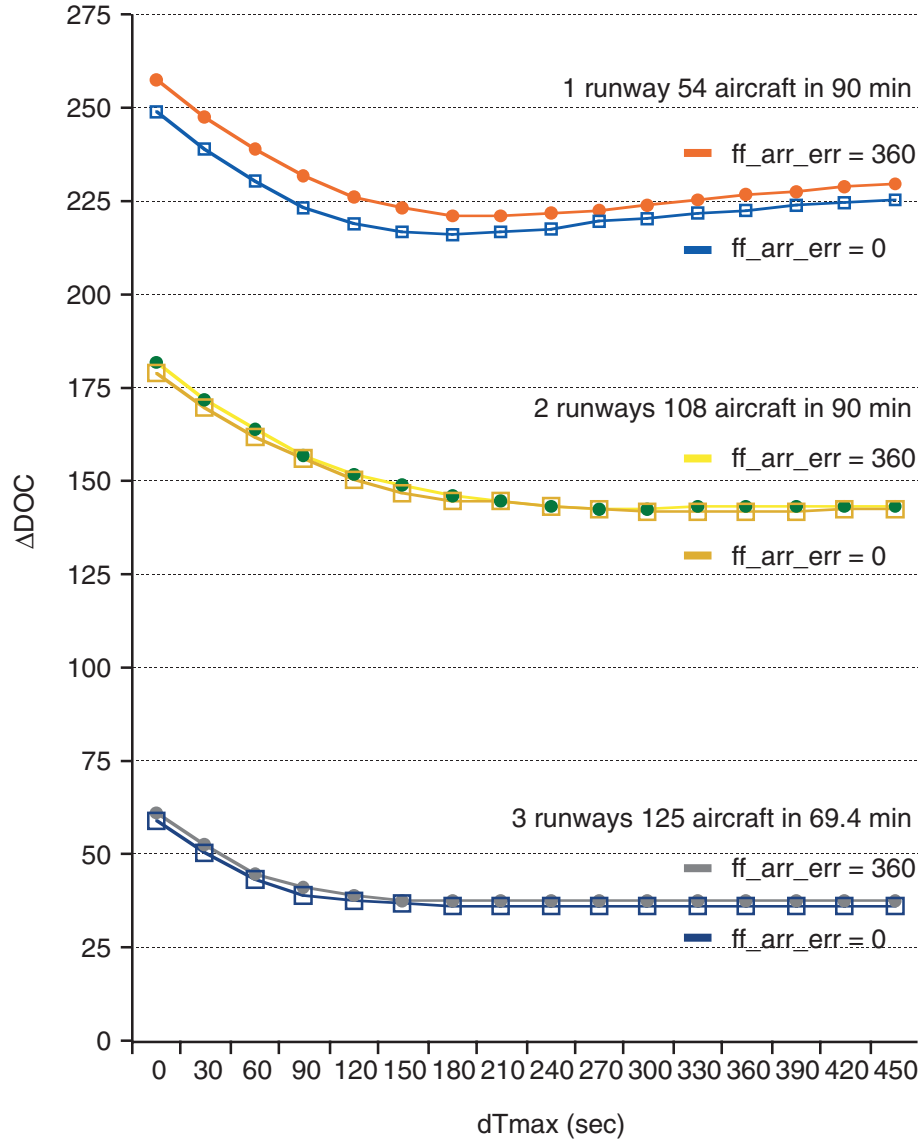
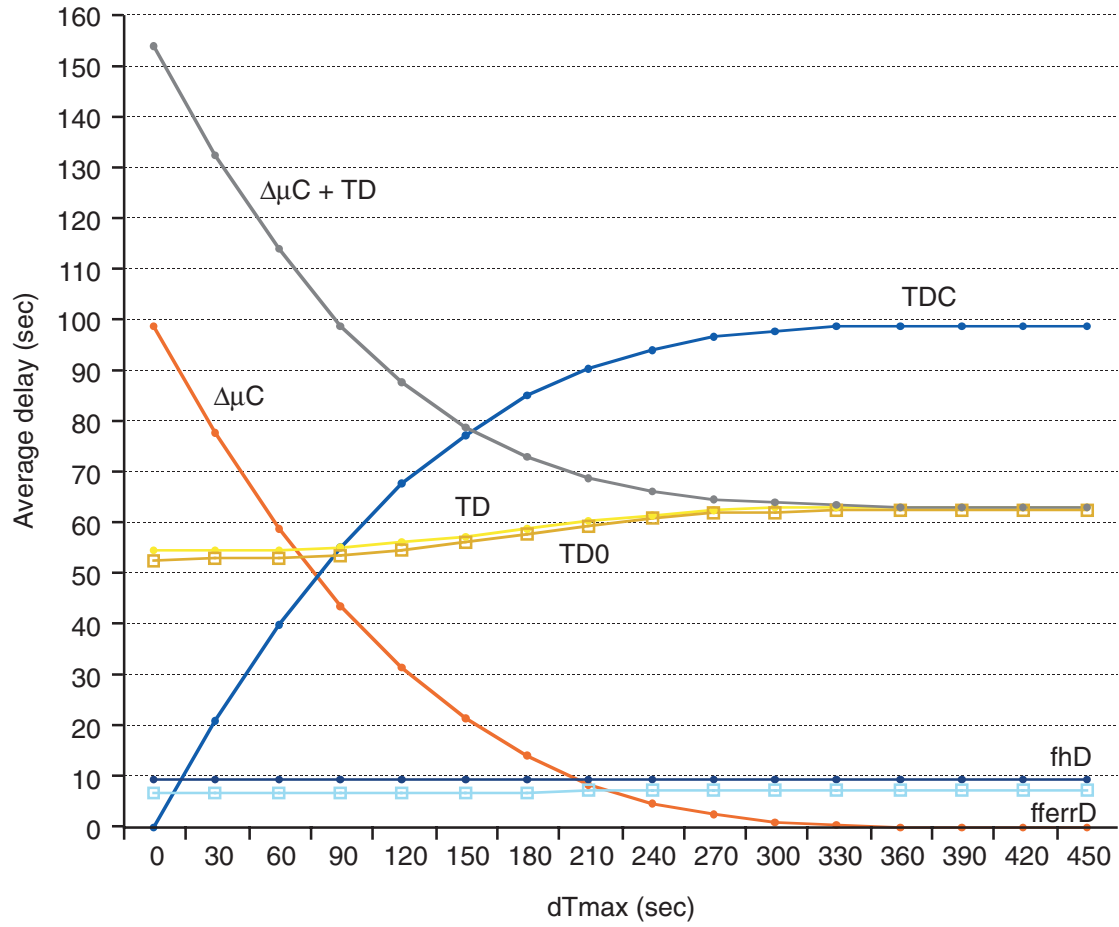
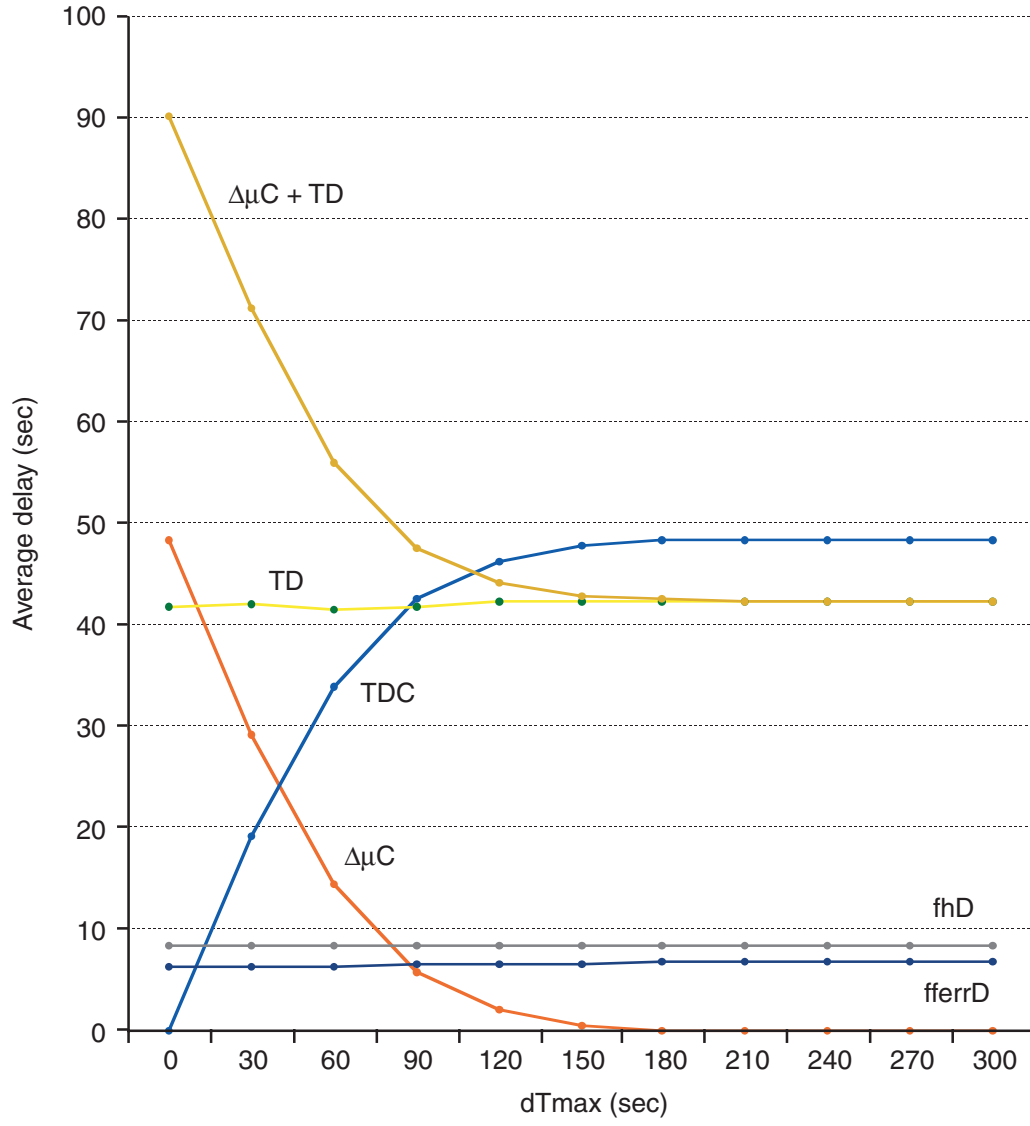


Figure 13.  $\Delta DOC$  for N aircraft in 90 min all with the same density = runway arrival rate.  
(For three runways, time was reduced to give the same runway arrival rate.)



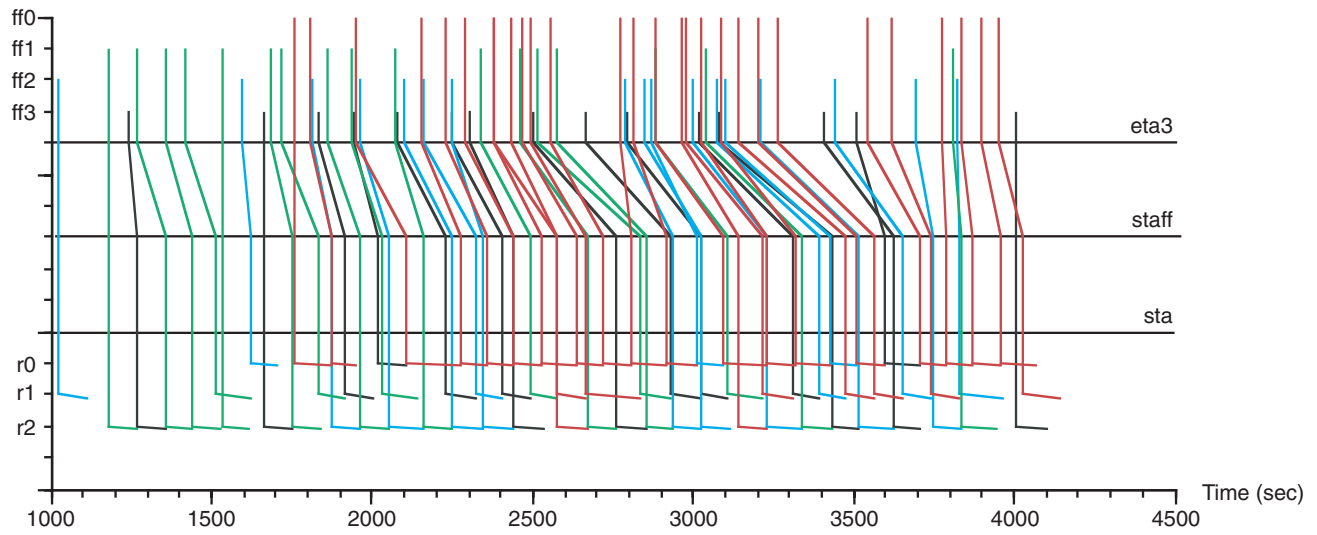
(a) Average delays from 1,000 nominal Noon Balloon samples: AAR = 300,  $r = 800$ ,  $r_2 = 360$  ( $r_2 = 0$  for TD0).

Figure 14. Comparison of average delays for nominal and squared Noon Balloon samples.

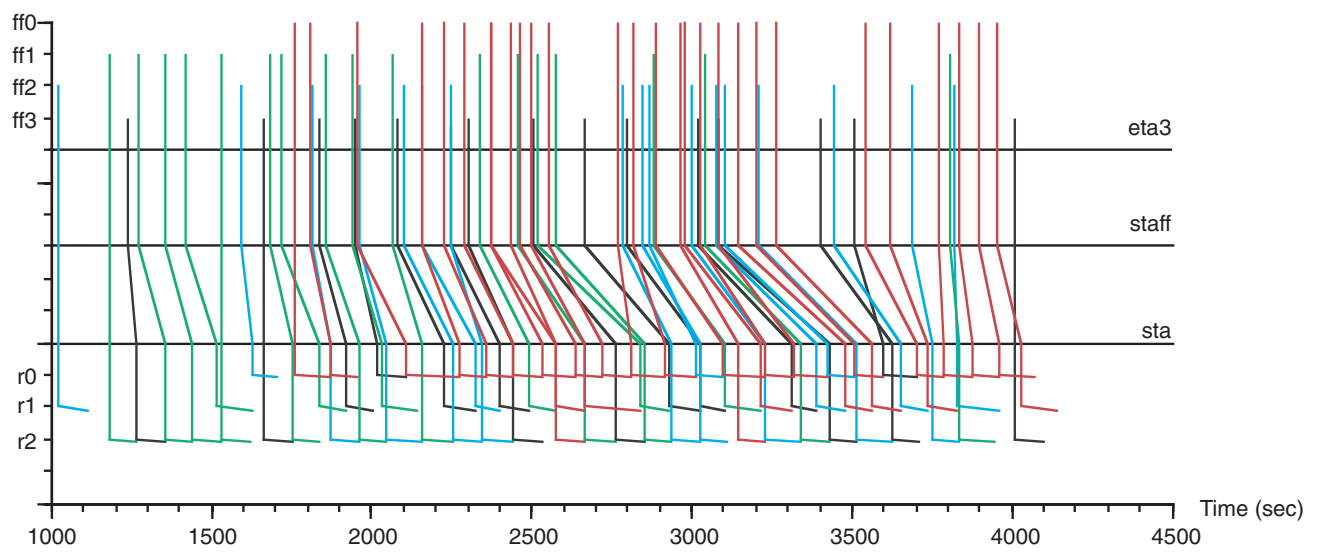


(b) Average delays from 1,000 squared Noon Balloon samples: AAR = 300,  $r = 800$ ,  $r_2 = 360$ .

Figure 14. Concluded.

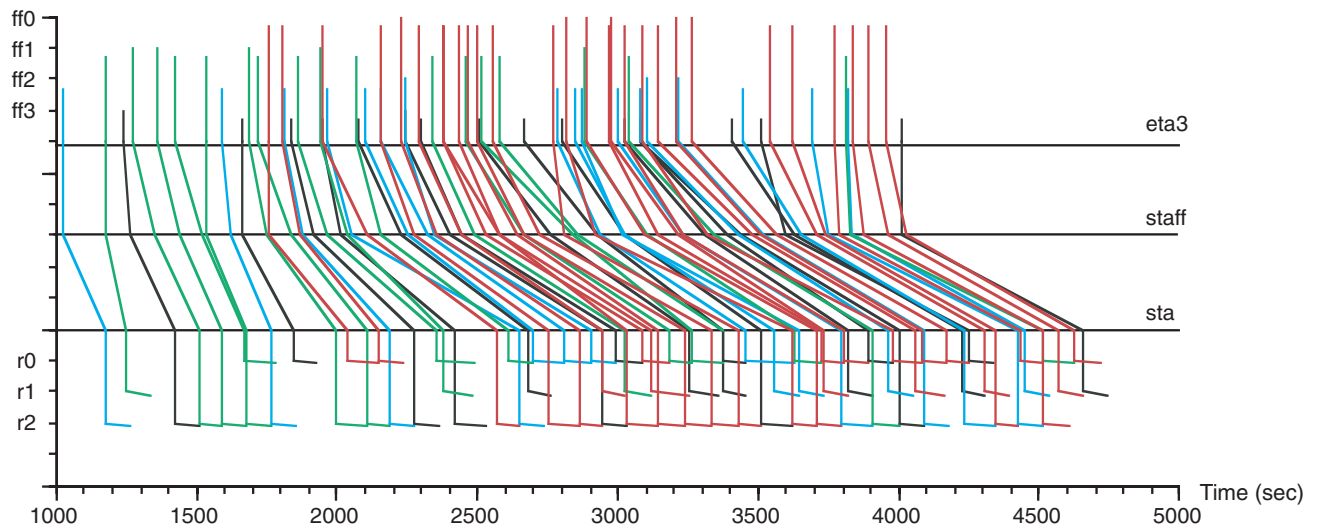


(a) Center schedule:  $dT_{\max} = 0$ .

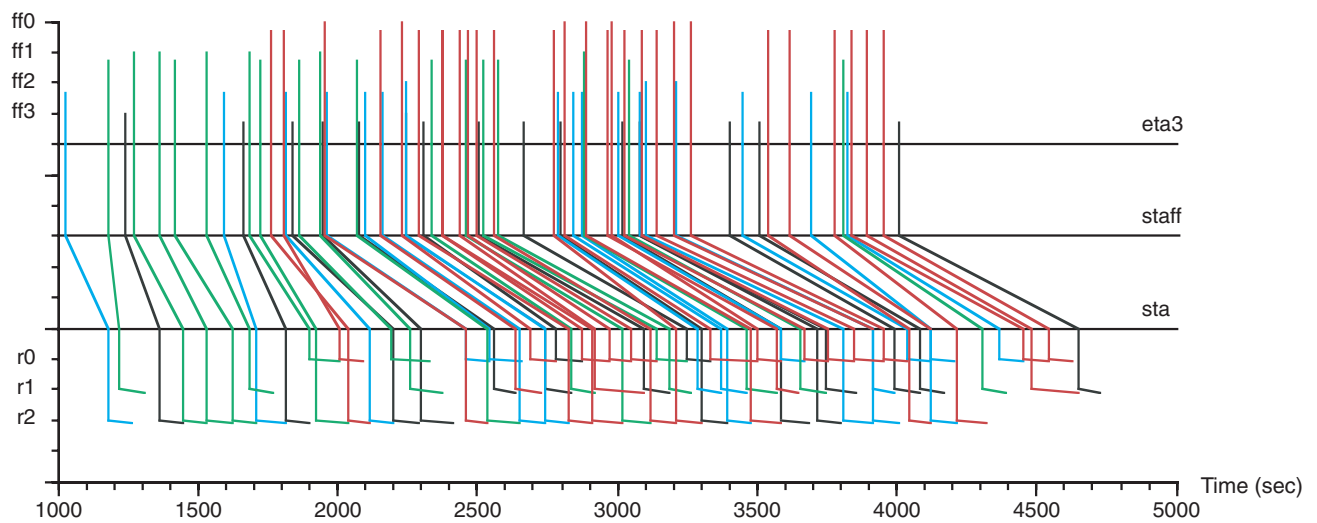


(b) Center schedule:  $dT_{\max} = 450$ .

Figure 15. Center schedule for different  $dT_{\max}$ .



(a) Center TRACON schedule:  $dT_{\max} = 0$ .



(b) Center TRACON:  $dT_{\max} = 450$ .

Figure 16. Schedule comparison for identical inputs (eta3) and different  $dT_{\max}$ .



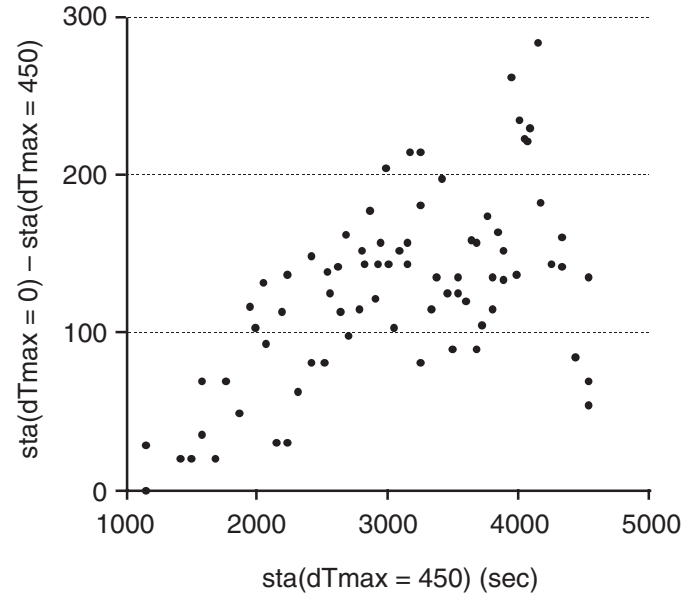


Figure 17. Comparison of delay differences for individual aircraft when scheduling at two dTmax.

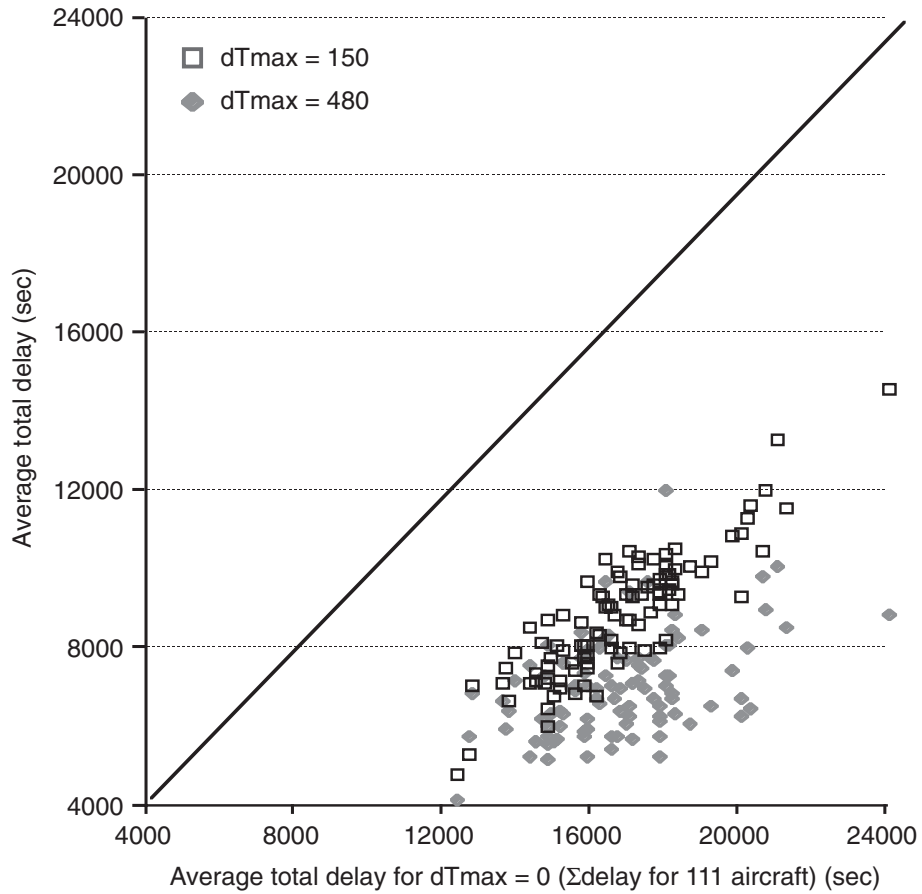


Figure 18. Delay comparison for three different dTmax.

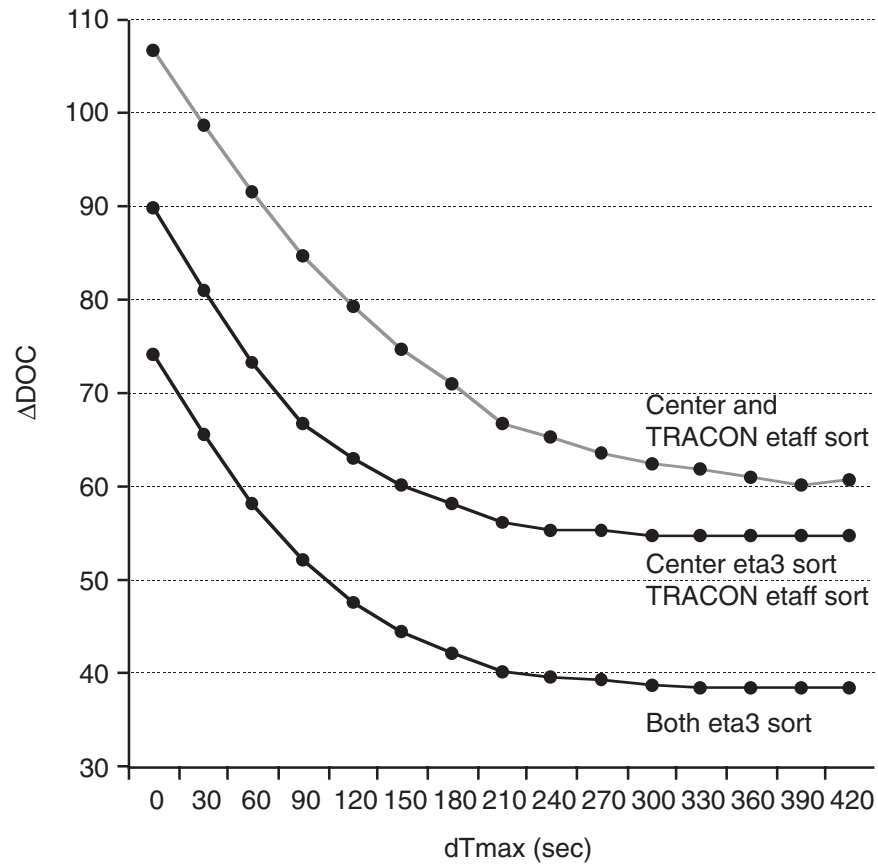
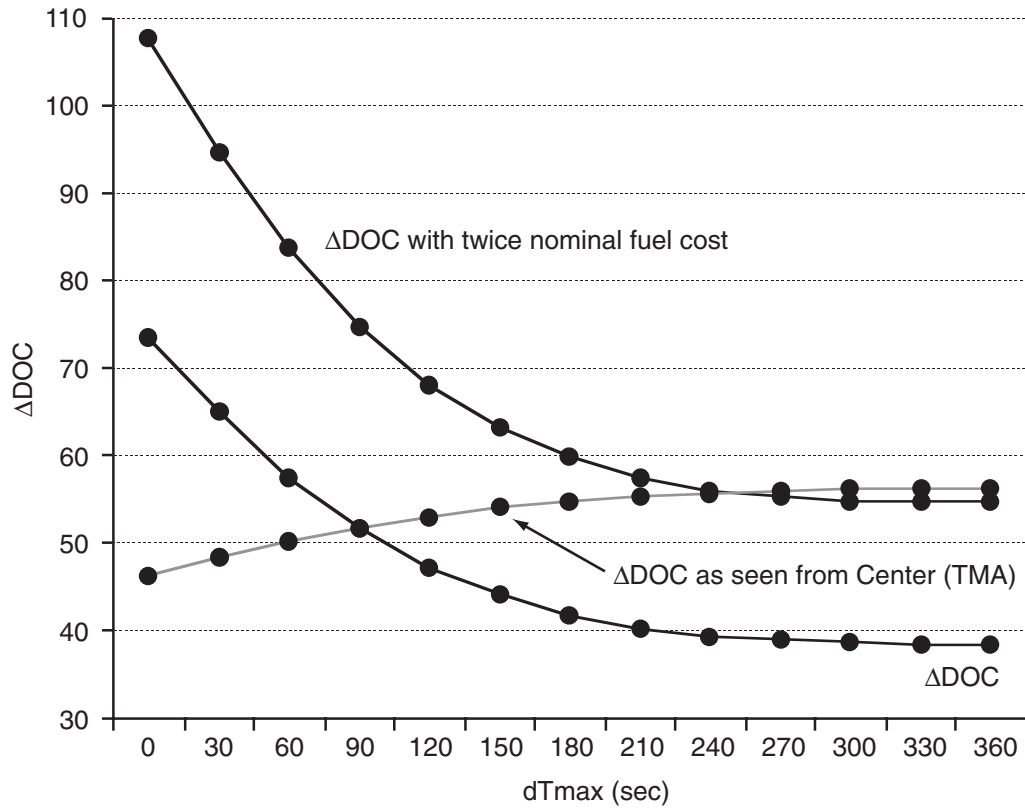
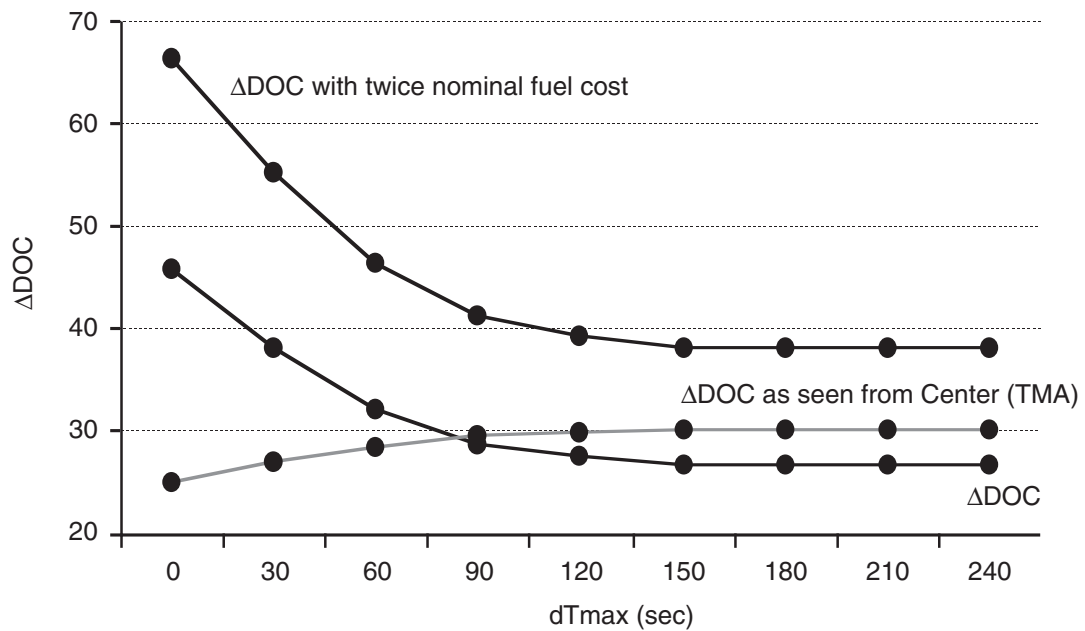


Figure 19. Demonstrating the advantage of scheduling in eta3 order in the Center and TRACON.

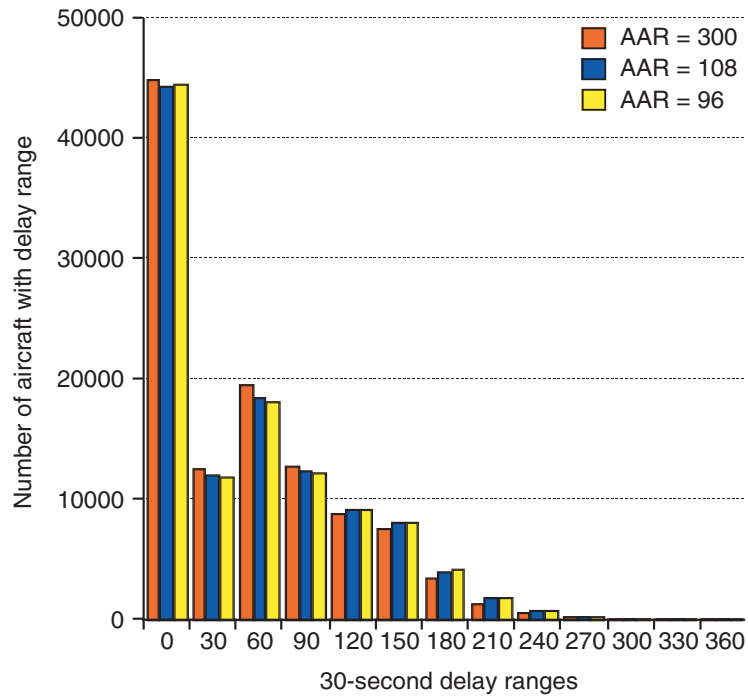


(a)  $\Delta$ DOCs for Nominal Noon Balloon when AAR = 300, ff\_aar\_err =  $\pm 180$  sec.

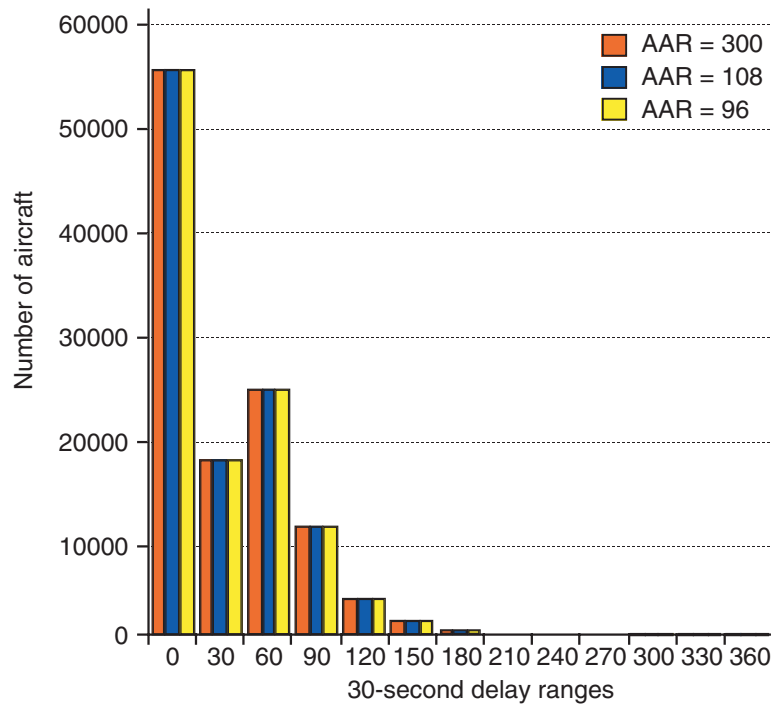


(b)  $\Delta$ DOCs for squared Noon Balloon when AAR = 300, ff\_arr\_err =  $\pm 180$  sec.

Figure 20.  $\Delta$ DOCs for nominal and squared Noon Balloon for identical conditions



(a) Nominal Noon Balloon.



(b) Squared Noon Balloon.

Figure 21. Comparison of TRACON delays for individual aircraft when all delays are transferred to TRACON (Center delay = 0 for large dTmax).



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